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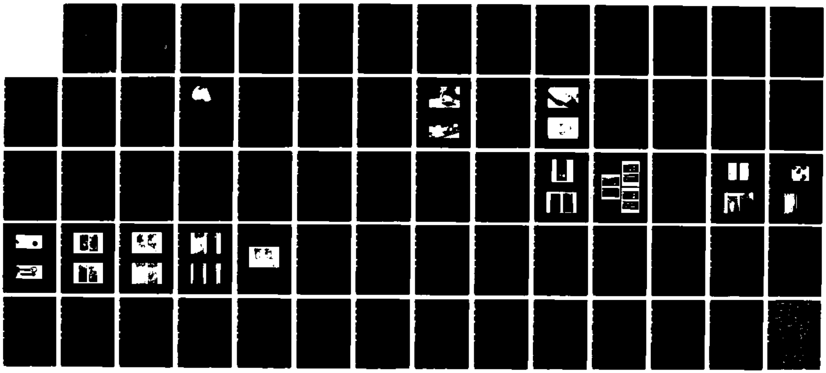

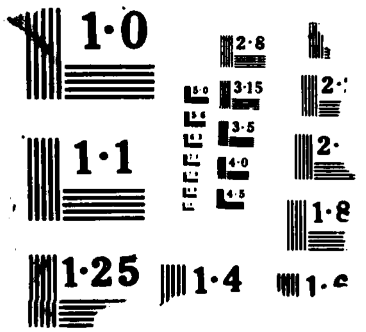
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USA-CERL TECHNICAL REPORT M-88/08
April 1988

AD-A195 153

Evaluation of Protective Coatings for Aluminum Torpedoes: Phase II

by
Susan A. Johnston

This report documents the second phase of research conducted to select, test, and evaluate protective coating systems for the Navy's MK 48 Torpedoes. Phase I of the research evaluated nine coating systems at different thicknesses and applied on different pretreated substrates. These results are documented in USA-CERL Technical Report M-329.

The Phase II program tested 10 additional coating systems, including conventional paint type coatings, powder systems, and ceramics. Testing evaluated the coatings' adhesion properties and their resistance to impact, gouging, and corrosion. The cumulative results of Phases I and II and forthcoming Phase III will provide critical inputs to determine the most effective protection to the MK 48 Torpedo. Phase I and II results indicate a powder epoxy is the best system tested to date.

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FOREWORD

This study was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USA-CERL) for the Naval Underwater Systems Center (NUSC) under MIPR N6660483WR30173, dated May 1983. The NUSC Technical Monitor was Mr. H. Pearl. The Navy Principal Investigators were Mr. K. J. Haydon (NAVSEA-PMS-402 F12) and Mr. J. R. Quartarone, NUSC. The USA-CERL Principal Investigator was Ms. Susan Johnston. Dr. R. Quattrone is Chief of USA-CERL-EM. Ms. Terry D. James, USA-CERL Information Management Office, was the technical editor.

COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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EVALUATION OF PROTECTIVE COATINGS FOR ALUMINUM TORPEDOES: PHASE II

1 INTRODUCTION

Background

In 1981, the U.S. Army Construction Engineering Research Laboratory (USA-CERL) began a cooperative effort with the Naval Underwater Systems Center (NUSC) to select, test, and evaluate protective coating systems for the Navy's MK 48 Torpedo--a long-range, high-speed, deep-depth weapon. The objective was to find the best protective coating system for the torpedo. The outer surface of the MK 48 is primarily made of 6000 and 7000 series aluminum, both of which are lightweight and strong, but have poor resistance to corrosion. On the submarine, the torpedoes are often kept in flooded tubes; therefore, a coating system must effectively protect the aluminum from corrosion by seawater. Also, since coating systems are frequently damaged during handling, the coating system must be tough and durable to reduce the high maintenance and repair costs associated with current MK 48 coatings.

USA-CERL previously evaluated nine potentially suitable candidate coating systems.[1] During Phase I of this research, the nine coatings were applied in three different thicknesses to three different pretreatments on 7075-T6 aluminum. The objective was to select an improved paint system. At the conclusion of the testing, NUSC asked USA-CERL to initiate a second phase of testing to evaluate additional coating systems.

Objective

Phase II of this study was designed to test a variety of coatings, including conventional liquid paint systems, powder systems, and ceramics. Future studies will be made to select an optimum protective coating system for the torpedo. The objective of Phase II was to quantitatively differentiate and rank the performance of these types of coatings.

Approach

NUSC selected 10 potentially suitable coating systems for testing. USA-CERL tested, evaluated, and ranked the coatings in order of their effectiveness. Physical and chemical tests were performed to examine the coatings' performance with regard to impact, adhesion, gouging, and corrosion resistance before and after immersion in synthetic seawater.

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[1] S. A. Johnston, *Protective Coatings for Aluminum Torpedoes*, Technical Report M-329/ADA133540 (U. S. Army Construction Engineering Research Laboratory [USA-CERL], 1983).

2 DESCRIPTION AND PREPARATION OF TEST SPECIMENS

Description of Coatings

NUSC selected 10 coating systems for testing (Table 1).* The systems chosen included both proprietary coatings and military specification materials that were expected to have high resistance to physical damage and corrosion in seawater. Six systems were conventional, wet-applied paint coatings. These were applied to hardcoat-anodized, dichromate-sealed aluminum and included polyurethane and epoxy systems. The remaining four systems were not conventional, wet-applied paint coatings. These were two plasma-sprayed, sealed ceramic-based coatings, a powder-applied epoxy, and a Teflon®-impregnated anodizing system. The following sections describe and provide manufacturer information for each of the 10 systems.

System 1: Clive Hare 9335 topcoat over Clive Hare 8799-A primer (NUSC identification number P/C-127). Primer #8799-A is a two-part vinyl/epoxy primer requiring the addition of a polyamide curing agent prior to application. It contains zinc potassium chromate corrosion inhibitor. Topcoat #9335 is a two-package vinyl/urethane topcoat in which an isocyanate curing agent is mixed with the pigmented resin base. These coatings were developed by Clive H. Hare, Inc., 79 Walnut Street, Stoughton, MA 02072. They were applied to 7075-T6 aluminum alloy panels, sandblasted and prepared with a 2 mil thick dichromate-sealed Type III hardcoat anodizing as described below.

System 2: Clive Hare 9335 topcoat over Clive Hare #8799-B primer (NUSC identification number P/C-128.) Primer #8799-B is a two-part vinyl/epoxy primer that requires adding a polyamide curing agent prior to application. It contains a nontoxic phosphate inhibitor rather than a chromate inhibitor. The topcoat and panel pretreatments are as described for System 1 above.

System 3: Deft MIL-C-83286** nonelastomeric aliphatic urethane coating over Deft #44-GN-7 primer (NUSC identification number P/C-125). The primer is a water-reducible epoxy primer with chromate corrosion inhibitors. The product is packaged in two components that are mixed at a ratio of three volumes of component I to one volume of component II. Six volumes (150 percent of the total volume of components I and II) of deionized or distilled water are then added to the mixture. An advantage of this primer is that it contains very small amounts of organic solvents, thus reducing safety and toxicity problems. The topcoat, Deft formula #03-W-40, is available in a gloss white, Fed. Std. 595 color #17925. The coatings were applied to 7075-T6 aluminum alloy panels, sandblasted, hardcoat-anodized and dichromate-sealed as described below.

System 4: 3M Epoxy 134 (NUSC identification number P/C-086). This powder-applied epoxy system was applied over a chromate film on lightly sandblasted 7075-T6 aluminum alloy test panels at a dry film thickness of 8 $\pm$ 1 mil.*** The coating was applied by Boyd Coatings, Inc., Hudson, MA, and supplied to USA-CERL as a finished product.

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*Tables and figures follow each chapter.

**Conforms to Military Specification (MIL-) C-83286B, *Coating Urethane, Aliphatic Isocyanate, for Aerospace Applications* (Department of the Army [DA], October 1973).

***Metric conversions are provided on p 51.

System 5: MIL-P-24441 modified formula. This system consists of an epoxy-polyamide primer based on Military Specification MIL-P-24441[2] Formula 158 and an epoxy-polyamide topcoat based on MIL-P-24441 Formula 152 (NUSC identification number P/C-126). The formulations were modified to replace 20 percent of the coating's Epon 815 resin component with Kelpoxy G293-100--an elastomeric, modified epoxy resin manufactured by Spencer Kellogg Division of Textron, Inc., P. O. Box 807, Buffalo, NY 14240. The modifications were intended to make the coating less brittle and thus increase the system's impact resistance. Only component B (the resin-containing component) of each formula was modified. Ratios for mixing components A and B* were changed by the modification. The paints were prepared at USA-CERL, using the formulas given in Appendix A. They were applied to 7075-T6 aluminum alloy panels, sandblasted, hardcoat-anodized and dichromate-sealed as described above.

System 6: Bostik MIL-C-83286[3] two-component nonelastomeric aliphatic urethane topcoat over Bostik MIL-P-23377[4] primer (NUSC identification number P/C-004). This system was tested during Phase I of the research, but the coating tested in Phase II was made by a different manufacturer: Emhart Chemical Group, Bostik Division, Middleton, MA 01949. The Bostik code numbers for these products are 463-7-26 for the primer and 643-18-4509 for the topcoat. They were applied to 7075-T6 aluminum alloy panels, sandblasted, hardcoat-anodized and dichromate-sealed as described above.

System 7: Bostik MIL-C-83286[5] nonelastomeric aliphatic urethane topcoat over Bostik BMS 10-11K Type 1 primer (NUSC identification number P/C-007). This is the current system used on the MK 48. The primer is an amine-cured epoxy coating meeting Boeing Aircraft specification BMS 10-11K. The primer is a readily available, conventionally pigmented coating. The Bostik code number for the primer is 463-6-3. The topcoat is the same as described for System 6. The coatings were applied to 7075-T6 aluminum alloy panels, sandblasted, hardcoat-anodized and dichromate-sealed as described above.

System 8: Metco 105SF (Al_2O_3) sealed with Vacuum Epoxy EPON 815/NUSC Catalyst Sealer (P/C-031). The ceramic coating was plasma-sprayed onto bare, sandblasted aluminum test panels at a nominal thickness of 10 $\pm$ 1 mil. This coating was applied by NUSC and supplied to USA-CERL as a finished product.

System 9: Metco 105SF (Al_2O_3) sealed with Loctite 290 Sealer (NUSC identification number P/C-032). The ceramic coating was plasma-sprayed onto bare, sandblasted aluminum at a nominal thickness of 10 $\pm$ 1 mil. NUSC applied the coating to the test panels and supplied them to USA-CERL as a finished product.

System 10: General Magnaplate Tufram H plus (NUSC identification number P/C-020). This coating was applied over bare, smooth aluminum test panels at a nominal film thickness of 4 mils. It was applied by General Magnaplate, Lydon, NJ, and supplied by NUSC to USA-CERL as a finished product.

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[2] MIL-P-24441A, *Paint, Epoxy-Polyamide, General Specification for* (DA, July 1980).
*Components A and B are defined in MIL-P-24441A.
[3] MIL-C-83286B.
[4] MIL-P-23377D, *Primer Coatings: Epoxy-Polyamide, Chemical and Solvent Resistant* (DA, 14 March 1978).
[5] MIL-C-83286B.

Preparation of Test Specimens

Aluminum Panels

All aluminum test specimens were 3- by 6- by 0.125-in. aluminum alloy 7075-T6. Except for the specimens that were supplied already coated (Systems 4, 8, 9, and 10), all of the test panels were made from the same batch of stock material. All edges were deburred and rounded. A single 1/4-in. hole was drilled in each specimen centered on the 3-in. side and 1/4 in. from the edge. Panels coated at USA-CERL were degreased, cleaned, and blasted with silica sand on all sides and edges to a white metal finish. The panels were then prepared with a 2 ± 0.5-mil-thick Type III, Class I, dichromate-sealed, hardcoat-anodized in accordance with MIL-A-8625C, 15 January 1968,[6] and Amendment I, 13 March 1969. The anodized specimens were supplied by The Metaspec Company, P.O. Box 27707, San Antonio, TX 78227.

The specimens provided by NUSC were not applied to anodized panels. Systems 4, 8, and 9 were applied to sandblasted, bare aluminum, and System 10 was applied to smooth, bare aluminum.

Coating Application

All of the coatings applied at USA-CERL were applied with Devilbiss conventional suction-cup air-spray equipment. The gun was operated at an air pressure of 40 psi and was equipped with a #30 air cap. None of the coatings required thinning to achieve a satisfactory film quality. Coatings were applied at the thicknesses recommended by the manufacturer or by the military specification. Table 2 gives additional information about the application of each coating.

Immersion

To simulate conditions under which the torpedoes are stored on Navy ships, the coatings were examined before and after a 90-day immersion in aerated synthetic seawater. One set of panels that had been coated with Tufram was immersed in a mixture of 50 percent Otto fuel and 50 percent seawater. The synthetic seawater was prepared from sea salt conforming to ASTM D 1141-52,[7] Table I, Section 4, Formula A, manufactured by Lake Products Co., Inc., St. Louis, MO.

Thickness Measurements. Prior to immersion, the dry film thickness of coatings was measured with a Zorelco "747" Digital Coating Thickness Gauge. This type of gauge induces eddy currents into the metal substrate of the specimen. Voltage varies with the thickness of the coating, and the gauge measures voltage changes across the probe coil. The gauge was zeroed and calibrated over uncoated aluminum panels of the same type as those to which the coating was applied (i.e., over anodized aluminum for the panels prepared at USA-CERL, and over sandblasted bare aluminum for the ceramic-coated panels). Film thickness was measured at three points on each side of each panel. Table 3 gives the mean coating thickness measurement values.

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[6] MIL-A-8625C, *Anodic Coatings, for Aluminum and Aluminum Alloys* (DA, 15 January 1968).

[7] ASTM D 1141-52, *Standard Specification for Substitute Ocean Water* (American Society for Testing and Materials [ASTM], 1952).

Galvanically Coupled Panels. Half of the 12 panels immersed were galvanically coupled to 2 brass panels of the same size as the specimen. Leads were soldered to the brass panels; a longer lead coupled one brass panel to the coated panel. Each coated panel was sandwiched between the two brass panels and bolted together using nylon nuts, bolts, and washers. Four washers were inserted between each panel to provide 1/8-in. spacing. The leads from the brass and coated panels were cut to 6 in., and the ends were stripped, twisted together, and soldered (Figure 1). The assembled panels were suspended in the tanks with the coupled ends of the wires well above the surface of the seawater. The length of the wires allowed the panels to be twisted apart enough to observe the condition and appearance of the coating during immersion.

Damaged and Undamaged Specimens. Prior to the testing, one-third (4) of the immersed coated specimens of each system were scored with a diamond-tipped scribe, one-third (4) were impacted prior to immersion, and one-third (4) were immersed undamaged.

Scored specimens were prepared with two parallel 3-1/2-in.-long scribe lines cut 1 in. apart on each face of the panel. Scribe lines were cut approximately 1 mm wide. The top of each scribe line was 1 in. from the top edge of the panel. On each panel, the left-hand scribe line was cut through to bare metal; the right-hand scribe line was cut through all layers of the paint coating to the anodizing (Figure 2). Where no anodizing was applied, both scribe lines were cut to bare aluminum.

Prior to immersion, selected panels were impacted with a Gardner Heavy-Duty Variable Impact Tester. Four points on each panel were impacted in predetermined locations with forces of 5, 10, 20, and 40 in.-lb, as shown in Figure 3.

Table 1

Summary of Coating Systems Tested

Phase II System No.	NUSC Ident. No.	Pretreatment	Primer	Topcoat	Total System Thickness* (mils)
1	P/C-127	anodized	Clive Hare 8799-A	Clive Hare 9335	8
2	P/C-128	anodized	Clive Hare 8799-B	Clive Hare 9335	7
3	P/C-125	anodized	H_2O Reducible Primer	Deft MIL-C-83286	6
4	P/C-086	bare	N/A	3M Epoxy 134	10
5	P/C-126	anodized	MIL-P-24441 Modified	MIL-P-24441 Modified	7
6	P/C-004	anodized	Bostik MIL-P-23377	Bostik MIL-C-83286	4
7	P/C-007	anodized	Bostik BMS 10-11K	Bostik MIL-C-83286	5
8	P/C-031	bare	N/A	Metco 105SF with EPON 815 Sealer	12
9	P/C-032	bare	N/A	Metco 105SF with Loctite 290 Sealer	12
10	P/C-020	bare	N/A	Tufram H plus	1

*Thickness includes anodizing, where applied.

Table 2

Coating Application*

Coating	Application Problems	Dry Film Thickness Per Coat (mils)	Pot Life (hr)
Clive Hare 9335	None	2.5	30
Clive Hare 8799-A	None	2.5	30
Clive Hare 8799-B	None	2.5	30
Deft MIL-P-83286	Air bubbles if applied too heavily	2.0	6
Deft #44-GN-7	None	2.0	4
MIL-P-24441 primer, modified	None	3.5	4
MIL-P-24441 topcoat, modified	None	3.5	5
Bostik MIL-C-83286	None	2.0	6
Bostik MIL-P-23377	None	2.0	8
Bostik BMS-10-11K	None	2.5	8

*Applies only to the systems applied in-house by USA-CERL.

Table 3

Mean Coating Thicknesses*

System No.	Coating	No. of Panels	Mean Thickness (mils)	Standard Deviation
1	Clive Hare 9335 over Clive Hare 8799-A	18	5.9	1.13
2	Clive Hare 9335 over Clive Hare 8799-B	18	4.8	0.55
3	Deft MIL-C-83286 over H_2O Reducible Primer	18	4.4	0.73
4	3M Epoxy 134	18	10.7	1.24
5	MIL-P-24441 Modified System	18	5.3	0.97
6	Bostik MIL-C-83286 over Bostik MIL-P-23377	18	1.5	0.35
7	Bostik MIL-C-83286 over Bosxtik BMS 10-11K	18	2.3	0.77
8	Metco 150SF with EPON 815 Sealer	18	11.7	0.50
9	Metco 150SF with Loctite 290 Sealer	18	11.6	0.75
10	Tufram H plus Batch 1	18	0.9	0.08
10	Tufram H plus Batch 2	12	3.1	0.25

*Measured thicknesses do not include anodizing, where applied.

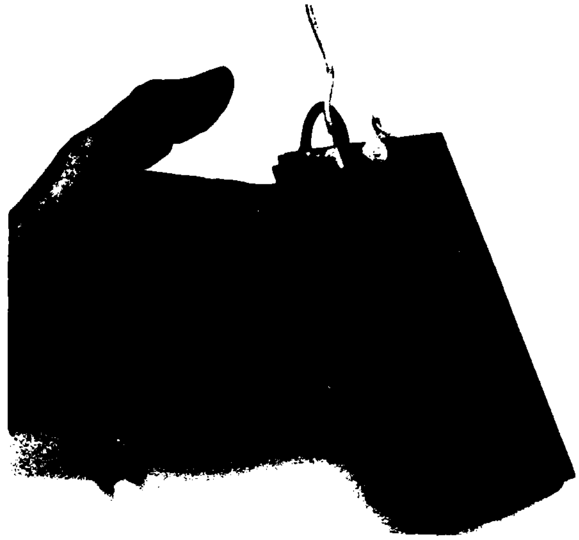

Figure 1. Galvanic coupling detail.

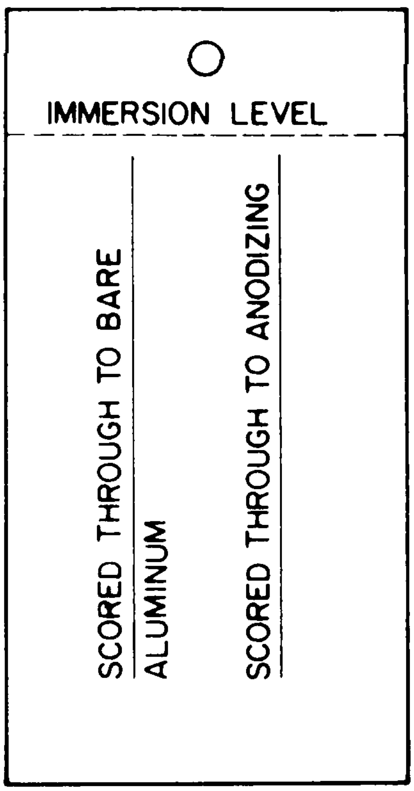

Figure 2. Placement of scribe lines.

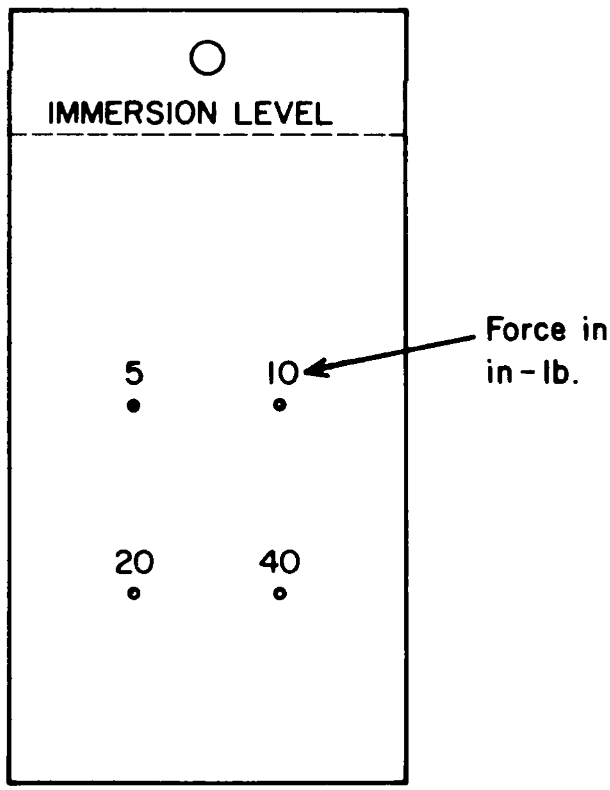

Figure 3. Location of preimmersion impact points.

3 TEST METHODS

Physical Test Procedures

Physical test procedures used in this Phase II evaluation are consistent with Phase I tests except in two cases. First, the impact test was modified to increase the upper limit of the testing range. This limit had been 80 in.-lb in Phase I. Additional weights were added to the apparatus to increase this upper testing limit to 210 in.-lb for Phase II. Second, the gouge test was modified significantly. The wire loop specified in the ASTM test method failed to give meaningful test results in some of the Phase I tests because the weight limit of the apparatus was reached before failure occurred. This wire loop was replaced by a tungsten carbide cutting tool, as described fully below.

Immersion Test

Panels were immersed for 90 days in either seawater or a 50/50 mixture of seawater and Otto Fuel.[8]

Elcometer Adhesion Test

The adhesion of each system before and after immersion in synthetic seawater was tested in accordance with the Elcometer Adhesion test method. A circular aluminum dolly was cemented to the surface of each coated panel with a high-strength epoxy adhesive (3M Scotch-Weld 1838 B/A) (Figure 4). The dollies were lightly sandblasted on the contact surface to ensure good adhesion. The coating surface was also slightly roughened with sandpaper. Weights were placed on the dollies while the adhesive cured. *All specimens were cured 18 to 24 hr at room temperature* before testing. The dolly was then pulled from the specimen with the adhesion tester, and the force required for separation was read in units of pounds per square inch.

Gouge Test

A gouge test was performed with a balanced-beam scrape adhesion tester (Figure 5). The method was based on ASTM D 2197-86,[9] Method A. Since the upper limit of the testing apparatus was too low to produce failure in the high-performance coatings tested, the method was modified. The hardened steel scraping loop was replaced with a radiused tungsten carbide cutting tool. The apparatus was modified to hold the cutting tool perpendicular to the coated surface (Figure 6). The tool, which has a curved cutting edge with a 1-in. radius, is designed to cut into most coatings at a very low load. The width of the cut then varies with the load applied and the toughness of the coating.

Tests were performed by making a series of 2-in.-long cuts into the coated surfaces with loads starting at 0.5 kg and increasing by 0.5 kg with each cut until a load was reached that caused the cutting tool to penetrate the coating system to the anodizing or to the aluminum substrate (Figure 7). In some cases, the upper limit of the testing apparatus was reached at a load of 12 kg before the substrate or anodizing was exposed. In other cases, the substrate was exposed at a very low load, and additional cuts were

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[8] *Otto Fuel II: Safety, Storage, and Handling*, NAVSEA OP 3368, Fifth Revision (Naval Sea Systems Command, 15 January 1973, Change 1, 15 May 1975).
[9] ASTM D 2197-86, *Test Methods for Adhesion of Organic Coatings by Scrape Adhesion Tester* (ASTM, 1986).

made at 0.1-g increments to provide more data points. A magnifying comparator equipped with a reticle calibrated in millimeters was used to measure the width of each cut at the surface of the coating to the nearest 0.1 mm. Three measurements were made at predetermined points along the length of each cut and averaged. Before beginning the test, three lines were drawn with a marker across the panel and perpendicular to the path of the cuts. Width measurements were made where each cut intersected these three lines. The marker lines also helped to define the boundary edges of the cuts for accurate measuring.

After every third specimen was tested, the sharpness of the cutting tool was gauged by cutting into the surface of a 1/4-in.-thick sheet of clear plexiglas with a load of 3 kg on the beam. The width of the gouge made in each specimen was compared to the width of the gouge made by the tool when it was new. The latter value was then divided by the first value to obtain a correction factor used to normalize the data for each specimen. The normalized cut widths were then used to calculate cut depths. Chapter 4 analyzes plots of cut width versus load.

Impact Test

An impact test was performed using apparatus as described in ASTM D 2794-84.[10] The test was performed at room temperature (25 $\pm$ 1°C) and again on specimens cooled to 4 $\pm$ 3°C for 1 hr. The test was done on a Gardner Heavy-Duty Variable Impact Tester (Figure 8). A specimen was set over a 0.640-in.-diameter hole in a die mounted on the base of the apparatus. A spherical tipped punch of 0.625-in. diameter was placed on the specimen. A weight was raised to a desired height (up to 40 in.) in a graduated tube. Two- and 4-lb weights were used separately and in tandem to deliver a maximum force of 210 in.-lb.

According to the test method standards, cracking of the coating constitutes impact failure. This end point works well with most common architectural coatings. However, since some coatings fail in other ways before they crack, the endpoint was chosen as any of the following types of failure: cracking on the impacted side, puncture of the topcoat (seen in elastomeric coatings), and debonding ("blistering") of the impact area. Cracking on the reverse of the panel was not considered a valid endpoint because a torpedo will not likely be impacted from the inside out to damage the exterior protective coating. Other details about the failure were also noted, such as whether the impact caused the rupture of the adhesion between the topcoat and primer or between the primer and substrate, etc. The failures were detected visually without magnification and by loosening ruptured coatings with a fingernail.

Chemical Test Procedures

Samples of each conventional liquid coating tested were submitted to USA-CERL for chemical characterization. Pigment content, total solids, and nonvolatile vehicle content of each coating component were measured. The results (Table 4) will provide a basis for comparing the batch used in this study with batches purchased in the future.

[10] ASTM D 2794-84, *Test Method for Resistance of Organic Coatings on the Effects of Rapid Deformation (Impact)* (ASTM, 1984).

Pigment Content

Test Method: Federal Test Method Std. No. 141B, Method 4021, 1 February 1979.

Apparatus: IEC International Centrifuge, Size 2, Model K, 8-unit head; Sartorius analytical balance.

Extraction mixture: 50 percent toluene, 50 percent acetone.

Procedure: About 15 g of the sample (coating or coating component) were weighed to the nearest 0.0001 g in a weighed centrifuge tube. Twenty-five mL of the extraction mixture were added and mixed thoroughly using a glass rod. The rod was washed with more of the mixture from a wash bottle. The material was centrifuged 30 min at 2000 rpm, and the clear supernatant liquid was decanted. These steps were repeated twice with 35 mL of the extraction mixture. After the liquid was drawn off for the last time, the tube was set in a steam bath for 10 min, put in a 105°C oven overnight, cooled in a desiccator, and weighed. The percentage of pigment was then calculated.

Total Solids

Apparatus: Sartorius analytical balance; aluminum evaporating dishes.

Procedure: About 0.5 g of the sample was placed in a weighed evaporating dish and quickly weighed to the nearest 0.0001 g. The dish was put in a 105°C oven for 1-1/2 hr, cooled, and weighed again. The percentage of total solids, by weight, was then calculated.

Nonvolatile Vehicle Content

Federal Test Method Std. No. 141B, Method No. 4053 (1 February 1980) was used to calculate the nonvolatile vehicle (NVV) content from the sum of volatile matter and the pigment solids content:

$$\%\ \text{NVV} = \frac{\%\ \text{total solids} - \%\ \text{pigment} \times 100}{100 - \%\ \text{pigment}}$$

The nonvolatile vehicle is the film-forming portion of the paint, i.e., the resins, plasticizers and other components of the dry film, excluding the pigments. A liquid (uncured) paint can generally be described as being made up of three components: the solvents, the pigments, and the nonvolatile vehicle.

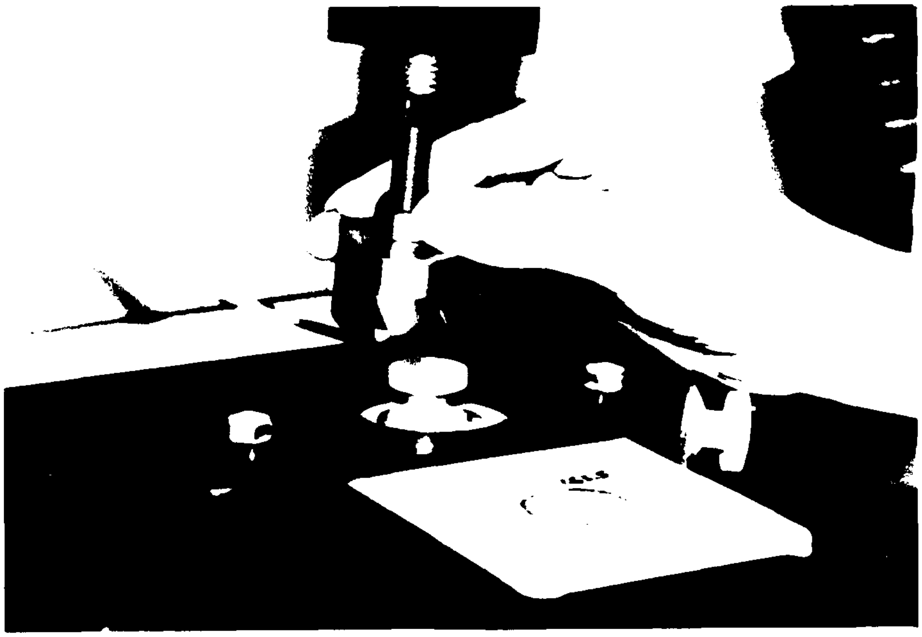


Figure 4. Elcometer dolly detail.

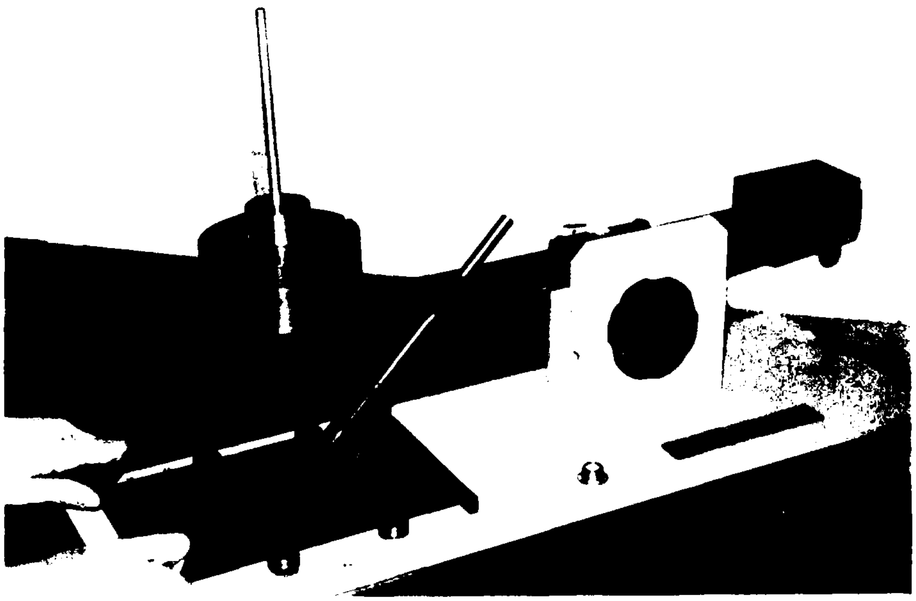


Figure 5. Scrape adhesion tester.

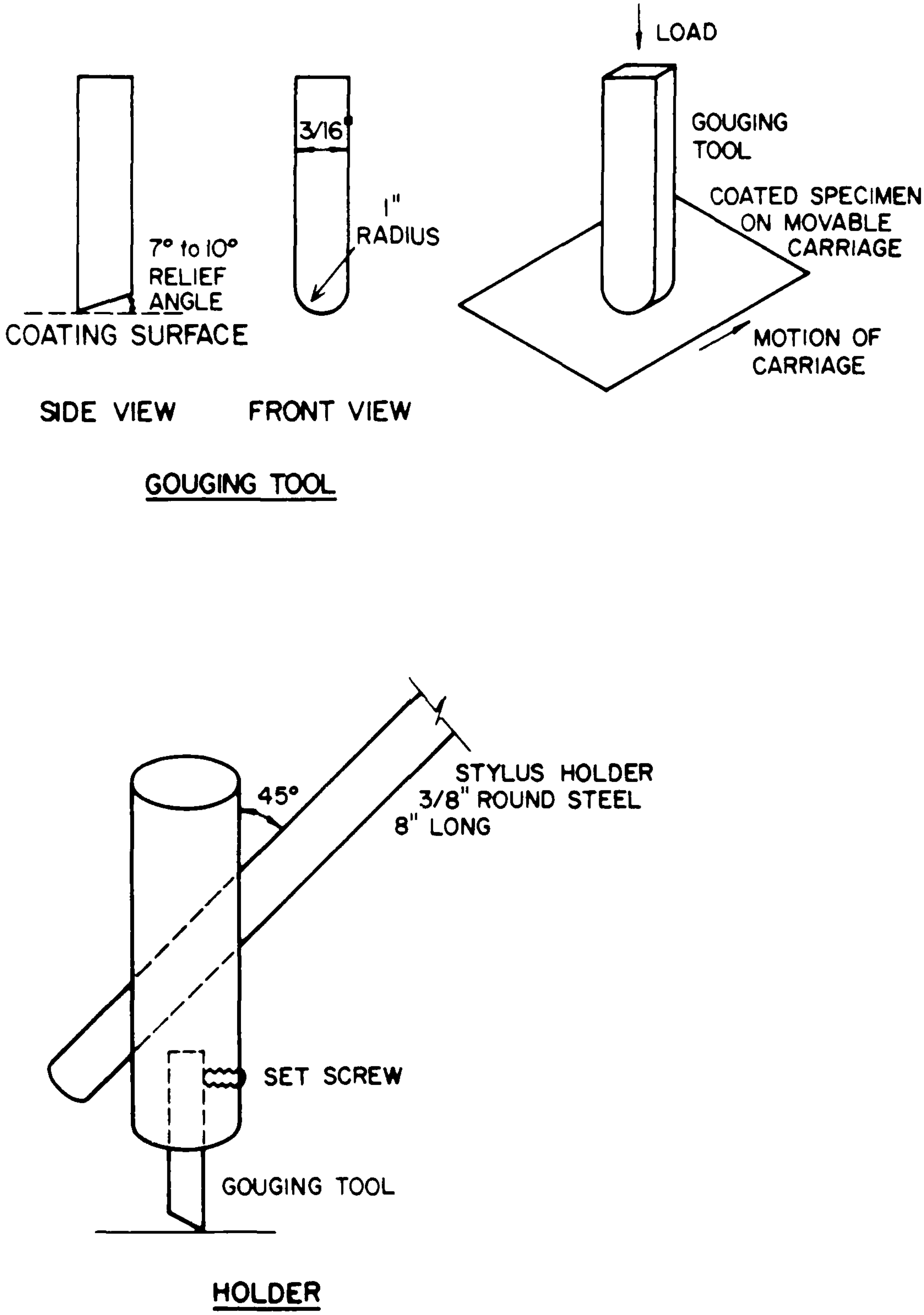


Figure 6. Gouging tool modification.

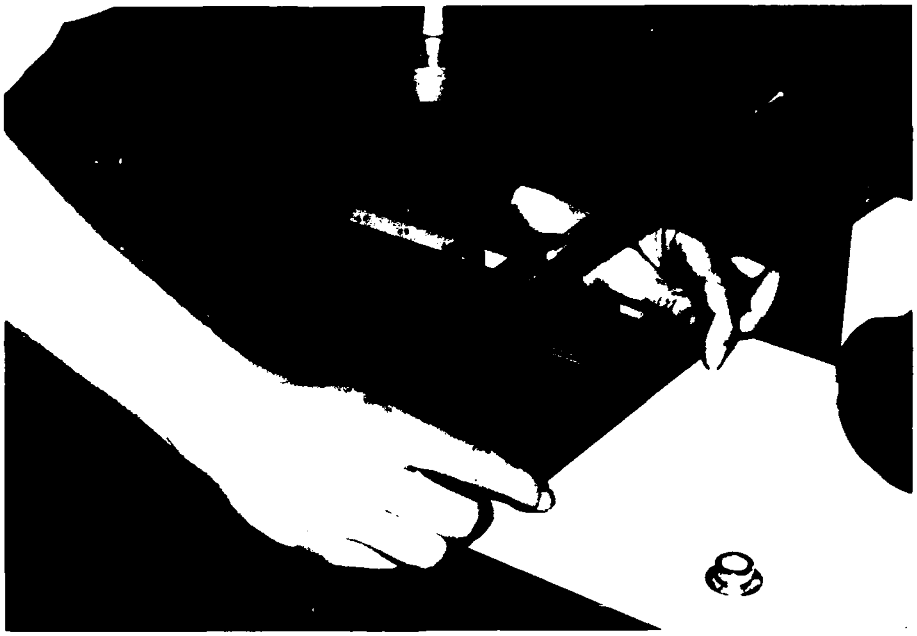


Figure 7. Gouge example.

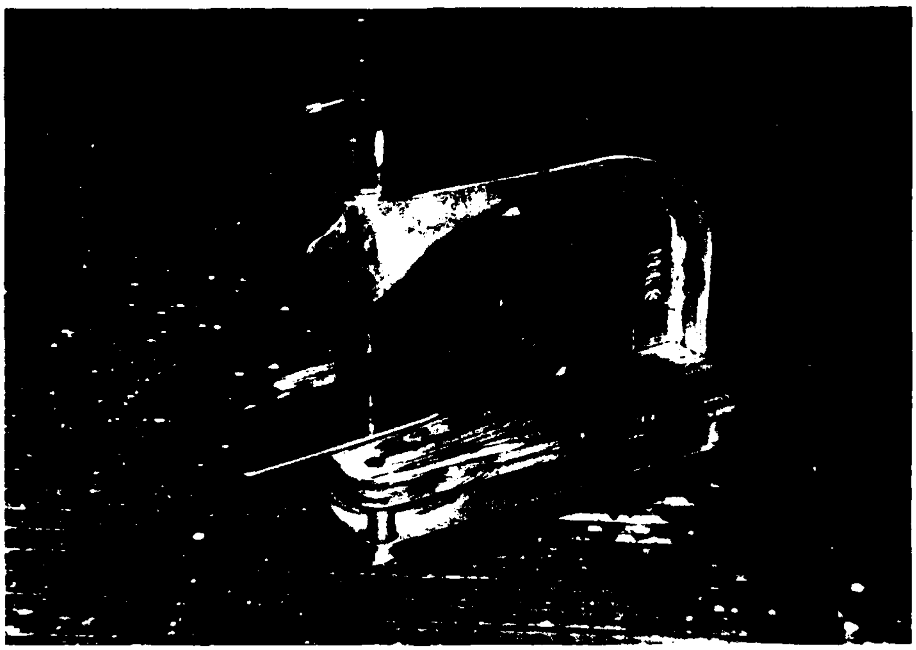


Figure 8. Impact tester.

Table 4

Chemical Characterization Test Results

Coating	Component	Total Solids Percent	Pigment Percent	Nonvolatile Vehicle Percent
Clive Hare 8799-A	A	67.5	35.9	49.3
	B	10.8	0.0	10.8
Clive Hare 8799-B	A	68.4	35.8	50.8
	B	11.1	0.0	11.1
Clive Hare 9335	A	78.9	37.5	66.3
	B	65.5	0.0	65.5
Deft Water-Reducible Chromate Primer	A	75.6	53.1	48.0
	B	85.5	0.0	85.5
Deft MIL-C-83286	A	70.0	33.7	54.8
	B	36.2	0.0	36.2
MIL-P-24441 Formula 158 Modified	A	73.3	50.6	46.0
	B	71.1	26.12	60.9
MIL-P-24441 Formula 152 Modified	A	69.3	48.7	40.2
	B	72.5	25.2	63.3
Bostik MIL-P-23377	A	62.9	13.6	39.6
	B	21.4	0.0	0.0
Bostik MIL-C-83286	A	56.6	13.6	49.8
	B	37.1	0.0	37.1
Bostik 463-6-3	A	47.3	30.1	24.6
	B	3.5	0.0	3.5

4 PHYSICAL AND IMMERSION TEST RESULTS

This chapter discusses the physical performance of coated specimens before and after immersion in synthetic seawater, as well as each coating's corrosion resistance during the testing. Care must be taken when comparing test results of different types of coatings, because modes of failure differed. For example, in the Elcometer Adhesion test, some coating systems broke cleanly from the substrate, while others broke between the primer and the topcoat. In the impact tests, some flexible coatings, such as the Clive Hare formulations, failed when the topcoat was punctured. Brittle coatings, such as MIL-P-24441, usually failed when the coating cracked at the impact point. Details on the failure mode of the coatings are included in test results where applicable.

Elcometer Adhesion and Impact Tests

With most types of coatings, the Elcometer Adhesion test dolly pulls all or part of the coating system from the panel. However, on some of the strongest coatings, the epoxy adhesive broke before the coating system failed, and the coating was left intact. The adhesion tester had a range of 0 to 1000 psi; the adhesive typically failed at 700 to 900 psi. Thus, no value could be obtained for coatings whose adhesion was greater than 900 psi. Additionally, the Tufram H plus coating system had such a smooth, slick surface that the adhesive did not adhere well, and the bond between the adhesive and the coating failed at about 300 to 350 psi.

Table 5 and Figures 9 through 11 summarize the results of Elcometer Adhesion and impact tests for the 10 coating systems. The results of duplicate tests have been averaged.

Statistical Analyses

Some of the physical test data were analyzed for significant differences by using t-tests. Pertinent averages of test results for the various coatings were compared. Tests of significance were conducted at the 0.05 level (i.e., it is 95 percent certain that the differences observed were significant).

1. System 1 versus System 2 (P/C-127 vs. P/C-128). These two systems were manufactured by Clive Hare and share the same topcoat. Both performed poorly during impact tests, with the topcoat cracking or chipping at a low impact force. However, the primer was left intact. System 2 performed better than System 1 in the Elcometer Adhesion test.

2. System 3 versus Systems 6 and 7 (P/C-125 vs. P/C-004 and P/C-007). Figure 12 summarizes the results of the tests on these three systems, which share the same topcoat specifications. System 6 (Bostik MIL-P-23377 primer with Bostik MIL-C-83286 topcoat) showed the best overall performance. System 3 (Deft #44-GN-7 primer with Deft MIL-C-83286 topcoat) ranked second, and System 7 (Bostik BMS 10-11K primer with Bostik MIL-C-83286 topcoat) was third. Results of the best two systems, compared by test, are as follows:

a. System 6 performed better than System 3 in the Elcometer Adhesion test. System 3 had a very low score for nonimmersed specimens and a high score for immersed specimens.

b. Systems 3 and 6 performed similarly in the impact test at 23°C as the difference was not statistically significant.

c. System 6 performed better than System 3 in the impact test at 4°C. The difference was statistically significant.

3. System 5 (P/C-126). This system (MIL-P-24441, modified) was compared to the unmodified MIL-P-24441 system tested in Phase I. The results of Phase I testing are reported in USA-CERL Technical Report M-329.[11] Figure 13 illustrates the comparison. The modified system showed increased resistance to damage by impact; results were 130 percent better at 23°C and 57 percent better at 4°C. Elcometer Adhesion test results were similar for the two systems.

4. System 4 (P/C-086). This coating was rated the best of the 10 systems evaluated. It was the only system to exceed the limits of both the impact tests and the Elcometer Adhesion test.

5. Ceramic Coatings. Differences in the results of the impact tests of Systems 8 and 9 (P/C-031 and P/C-032) were not statistically significant. However, System 8 specimens did give significantly better results than System 9 specimens in the Elcometer Adhesion tests. System 8 did not fail within the limits of this test, but System 9 failed the test because there was a cohesive break of the ceramic layer. However, the aluminum substrate was not visibly exposed by the failure.

6. Tufram H plus (System 10, P/C-020). The Elcometer Adhesion test results for the Tufram H plus system appeared to be very good; the coating did not fail within the test limits. However, the test adhesive used to bond the dolly to the surface did not adhere well to the slick surface of the coating; the test adhesive failed at about 300 to 350 psi, rather than at the 700 to 900 psi range expected for most coatings. The coating performed as well as many of the other systems in the impact tests before immersion. However, after immersion in seawater and in the seawater/Otto Fuel mixture, the results were poor.

Gouge Tests

Table 6 and Figure 14 summarize the results of the gouge tests. Appendix B gives plots of the gouge test results; the cut width (in millimeters) is plotted versus load (in kilograms) for each specimen. A steeper slope indicates a poorer gouge resistance while a lesser slope shows a better gouge resistance.

Linear regression analysis gave the best representation of the data. For primer/topcoat systems, one line represents the load range in which only the topcoat was penetrated, and the other represents the range in which the tool was cutting through the topcoat into the primer. Two specimens from each coating system were tested; one had been immersed in seawater and one had not. A third specimen of Tufram H plus that had been immersed in the seawater/Otto Fuel mixture was also included.

Table 6 lists the load required to penetrate (1) through the topcoat to the primer (where applicable) and (2) through the topcoat to the anodizing. Data are given both for panels that were not immersed in seawater and for those that were immersed for 90

[11] S. A. Johnston.

days. The results (Figure 14) show that four systems (4, 8, 9, and 10) were not penetrated by the cutting tool at a load of 12 kg, the maximum for the balance beam apparatus. System 4 (3M Epoxy 134) was gouged by the cutting tool, but was both tough and thick. Systems 8 and 9 (the ceramic systems) were not gouged by the cutting tool; the tool merely rode along the surface of the ceramic and did not penetrate the coating. Similarly, System 10 was marred by the cutting tool without actually being gouged, except that the tool made a few small nicks in the coating. A more complete comparison of the gouge resistance of these four systems must include an analysis of the graphs plotted in Appendix B. The graphs show how rapidly the penetration point was reached with increasing load on the beam. A greater slope indicates the coating was more resistant to gouging. System 4 graphs show a line with a slope of about 1.2×10^{-4} mm/kg, while System 10 graphs show a line with a slope of only 1.3×10^{-5} mm/kg. Systems 8 and 9 were not damaged under any load and were not plotted. If plotted, the line would have a slope of zero and a y-intercept of zero, and no failure point within the limits of the testing apparatus.

Of the remaining six systems, System 5 (the MIL-P-24441 modified system) had the greatest gouge resistance; a loading of 7.0 kg was required to penetrate to the anodizing. Systems 3, 6, and 7--the three systems with the MIL-P-83286 topcoat--had the poorest resistance to gouging.

Immersion Tests

Since many coatings fail in the range of 5 to 40 in.-lb, several panels had at least one actual coating failure among the four points of impact. Figure 15 shows a specimen that showed heavy corrosion at the point impacted with a force of 40 in.-lb and less corrosion at the 20 in.-lb point. The specimen was galvanically coupled to brass and had been immersed in seawater for 90 days. The remaining panels immersed in synthetic seawater were not damaged before immersion. Table 7 summarizes the results of the immersion tests on galvanically coupled and uncoupled test specimens.

The condition of each panel was then rated according to the following criteria:

Excellent: No visible damage to the aluminum substrate. Impact points are not corroded or pitted, although the paint surface may be damaged. The score lines may have some oxides, but there is no pitting or widening of the lines.

Good: Less than 5 percent of the surface area is corroded. The 20- or 40-in.-lb impact points show some corrosion extending not more than 1/8 in. from the center of the impact point. Score lines widen to no more than 1/8 in. across.

Fair: Five to 8 percent of the surface area of the specimen is corroded. The 20- and 40 in.-lb impact points show corrosion 1/8 to 1/4 in. from the center of the impact and usually show a penetration through the panel. Five- and 10-in.-lb impact points show a smaller area of corrosion. Score lines widen up to 1/4 in. across and may contain some areas of penetration through the panel.

Poor: More than 8 percent of the specimen's surface area is corroded. Forty- and 20-in.-lb. impact points are corroded more than 1/4 in. from the center of the impact point and penetrate through the panel. Five- and 10-in.-lb impact points may also penetrate through the panel. Score lines widen to more than 1/4 in. across and penetrate the panel along much of their length.

These immersion rating criteria were used for both damaged and undamaged specimens and for specimens that were and were not galvanically coupled. Figure 16 gives examples of specimens illustrating the rating criteria. Some of the impacted panels did not corrode when the coating was chipped but the anodizing was left intact. These specimens met the criteria for "excellent" immersion resistance.

Some score lines that were cut to bare aluminum did not corrode significantly during immersion. When the bare aluminum is exposed to seawater, some oxides form on the surface of the metal. A scored panel could still meet the criteria for excellent immersion resistance if the corrosion has not extended beyond the original score line in width or in depth. Most of the nongalvanically coupled scored specimens and some of the coupled specimens were able to meet these criteria. This may have been due to the corrosion-inhibitive properties of the coatings and the aluminum pretreatments.

1. System 1 versus System 2 (P/C-127 vs. P/C-128). Both damaged and undamaged uncoupled specimens of both systems were highly resistant to corrosion. These panels were rated excellent. System 2 undamaged, coupled specimens were rated excellent, while System 1 undamaged, coupled specimens were only rated good. System 1 panels corroded at the corners, but System 2 panels did not visibly corrode (Figures 17 and 18). Damaged coupled specimens for both systems showed equal performance, and were rated fair.

2. System 3 versus Systems 6 and 7 (P/C-125 vs. P/C-004 and P/C-007). Both damaged and undamaged uncoupled specimens for all three systems showed excellent performance. However, coupled panels of all three were rated only fair to poor. Corrosion undercut the paint films, stripping the paint from the panel over as much as 80 percent of the surface (Figure 19). System 7 performed somewhat better than the other two systems.

3. System 4 (P/C-086). Both damaged and undamaged uncoupled specimens had excellent resistance to corrosion. Undamaged coupled specimens corroded only where the coating was not continuous around the hole drilled in the top of the specimen (Figure 20). However, this type of damage is of no concern, and these were rated excellent. Damaged coupled specimens also corroded around the hole. Impacted specimens corroded at the 40-in.-lb impact point on the reverse of the panel, leaving a deep pit in the aluminum and undercutting the coating for a 1.5-in. radius around the impact point. On the impacted side of the panel, a smaller pit was formed and the coating was undercut for a 0.5-in. radius around the impact point (Figure 21). Scored panels pitted deeply along the score line. The coating was undercut by corrosion from 0.25 to 0.75 in. wide along the score lines (Figure 22). The damaged coupled specimens, both scored and impacted, were rated poor.

4. System 5 (P/C-126). This system had excellent corrosion resistance on both damaged and undamaged uncoupled panels, as well as on the undamaged coupled panels. Impacted coupled panels corroded at the 10-, 20-, and 40-in.-lb impact points, and corrosion undercut the film on 50 percent of the surface area of these panels (Figure 23). These panels were rated poor. Scored coupled specimens pitted deeply along the score lines and were rated fair.

5. Ceramic Coatings. Uncoupled specimens of both ceramic systems were rated good to excellent. Uncoupled, impacted panels sealed with Epon 815 (System 8, P/C-031) had some corrosion under the coating, but not pitting; these were rated good. Uncoupled panels sealed with Loctite (System 9, P/C-032) had some minor pitting and were also rated good.

Coupled, undamaged panels sealed with Epon 815 corroded only around the hole drilled at the top and were rated good. Similar panels sealed with Loctite were rated poor due to minor pitting over about 30 percent of the area and corrosion that undercut about 50 percent of the coating and loosened it from the aluminum (Figure 24). The system sealed with Epon 815 also had better performance than the Loctite-sealed panels on damaged, coupled panels, although both systems were rated poor in this category. Impacted panels pitted the coating and corrosion undercut it to a radius of 0.6 in. around the 20- and 40-in.-lb impact points on the panels sealed with Epon 815. The Loctite-sealed panels corroded at all four impact points, and the panels showed severe pitting. About 50 percent of the coating area was undercut by corrosion (Figure 25). Scored panels sealed with Epon 815 pitted along the score line, and corrosion undercut the film to 0.5 in. on each side of the score line. Scored panels that had been sealed with Loctite pitted and corroded more severely.

6. Tufram H plus (System 20, P/C-020).

a. Seawater. Uncoupled panels were rated excellent for both damaged and undamaged specimens. Coupled panels were all rated poor. Both damaged and undamaged coupled panels showed severe pitting over much of the surface, especially at the top of the panel at the air/water interface (Figures 26 through 28). Impacted panels corroded at all four impact points. Scored panels pitted along the score lines, but the film was not undercut by corrosion beyond 0.1 in.

b. Seawater/Otto Fuel Mixture. Uncoupled specimens corroded at the 40-in.-lb impact points and score lines; undamaged panels showed some very slight pitting. All uncoupled panels were rated good. Coupled panels corroded on the top half, which was in the water layer of the two-layer mixture. Corrosion was severe, and much of the metal was lost. Score lines penetrated through the panel (Figure 29).

Table 5

Physical Test Results

	System		Elcometer Adhesion Test (Hundreds of lb/sq in.)	Adhesion* Failure Type (in.-lb)	Impact** Test (23°C) (in.-lb)	Impact** Test (4°C) (in.-lb)	Impact Failure Type
1	Clive Hare 9335 over Clive Hare 8799-A	Not Immersed: Immersed:	5.6 4.5	Within primer layer	6 6	9 8	Debond between primer and topcoat
2	Clive Hare 9335 over Clive Hare 8799-B	Not Immersed: Immersed:	7.8 6.5	Within primer layer	7 6	7 4	Debond between primer and topcoat
3	Deft MIL-C-83286 over H_2O Reducible Primer	Not Immersed: Immersed:	1.9 8.5	Between primer and substrate	210+ 174	122 85	Debond between substrate and primer
4	3M Epoxy 134	Not Immersed: Immersed:	+ +	N/A	210+ 210+	210+ 210+	N/A
5	MIL-P-24441 Modified System	Not Immersed: Immersed:	7.4 8.1	Between primer and substrate	71 49	48 37	Debond between substrate and primer
6	Bostik MIL-C-83286 over Bostik MIL-P-23377	Not Immersed: Immersed:	+ +	N/A	194 173	186 151	Debond between substrate and primer
7	Bostik MIL-C-83286 over Bostik BMS 10-11K	Not Immersed: Immersed:	4.1 4.1	Within primer layer	81 37	63 19	Debond within primer layer
8	Metco 150SF with EPON 815 Sealer	Not Immersed: Immersed:	+ +	N/A	31 32	24 30	Ceramic cracked and chipped
9	Metco 150SF with Loctite 290 Sealer	Not Immersed: Immersed:	4.8 6.6	Within ceramic layer	31 35	23 32	Ceramic cracked and chipped
10	Tufram H plus	Not Immersed: Immersed: 50/50 Seawater + Otto Fuel:	+ + +	N/A	84 34 24	56 39 25	Debond coating from substrate

*A "+" indicates that the test adhesive broke before the coating failed.
**The maximum limit of the testing apparatus was 210 in.-lb. A value of 210+ indicates that failure did not occur at 210 in.-lb.

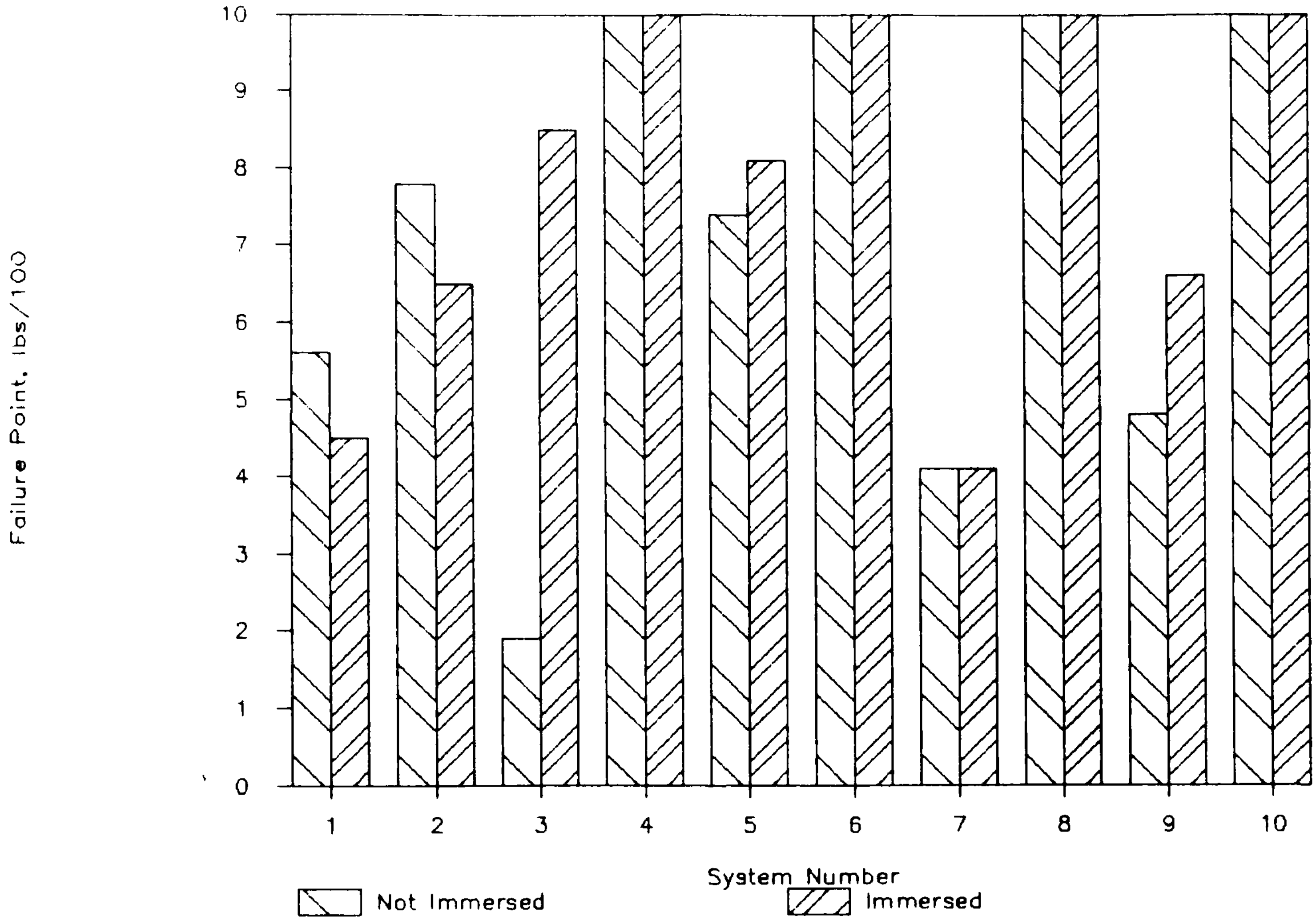


Figure 9. Elcometer bar graph.

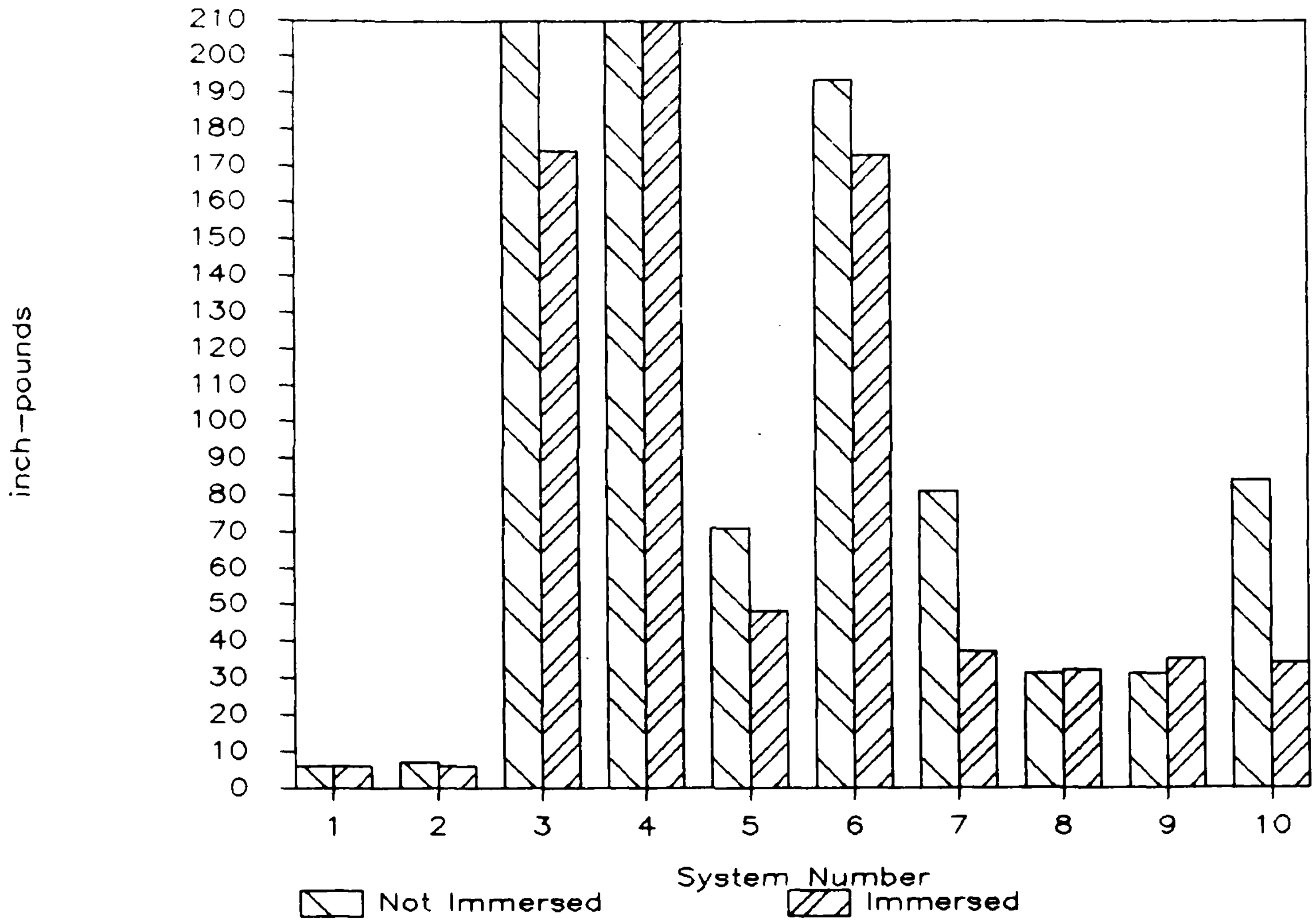


Figure 10. Impact test 23°C bar graph.

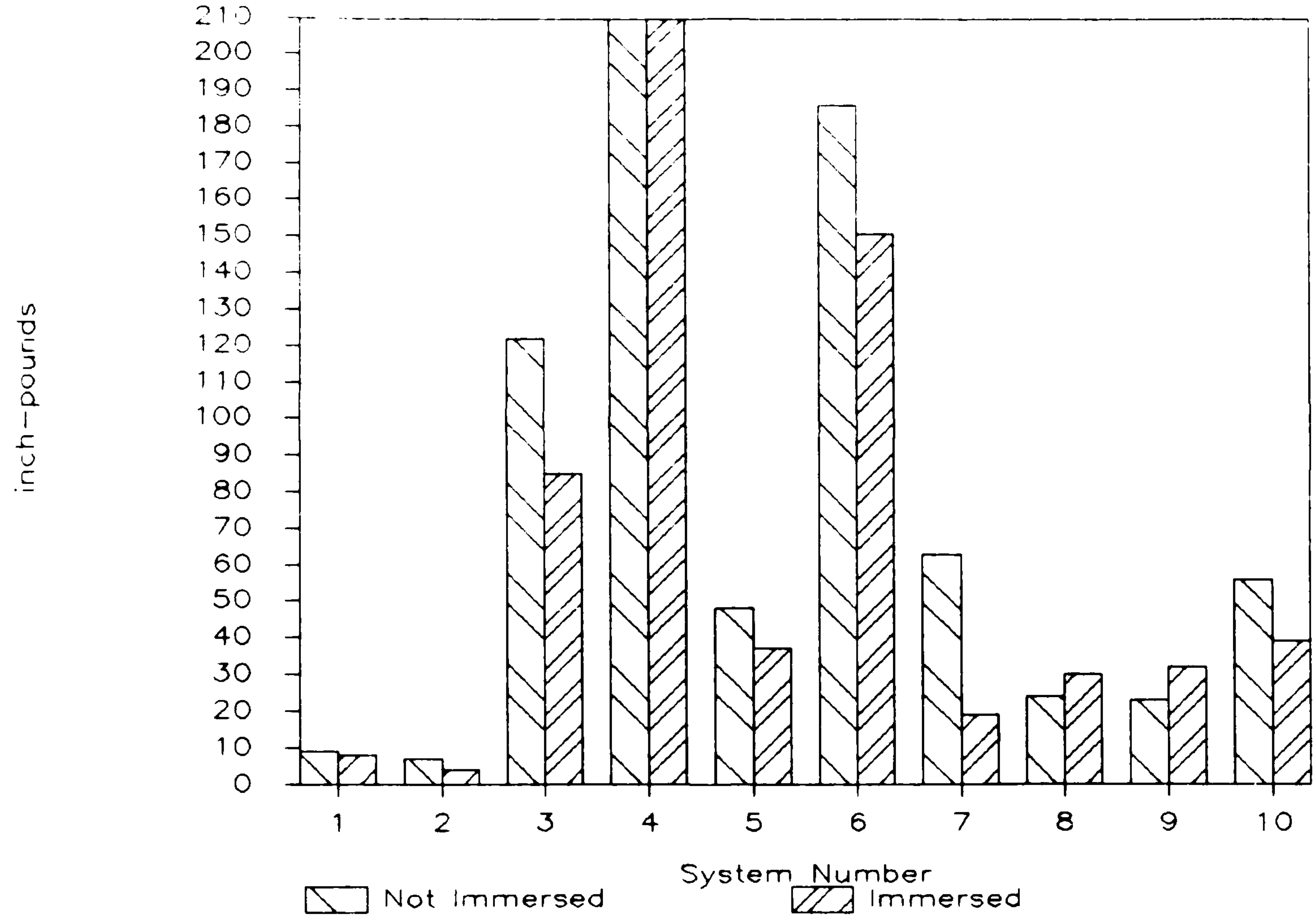


Figure 11. Impact test 4°C bar graph.

	System 3		System 6		System 7	
	Deft Water-Reducible Primer		Bostik MIL-P23377		Bostik BMS 10-11K	
	Immersed		Immersed		Immersed	
	No	Yes	No	Yes	No	Yes
Elcometer Adhesion	1.9	8.5	+	+	4.1	4.1
Impact, 23°C	210+	174	194	173	81	37
Impact, 4°C	122	85	186	151	63	19

Figure 12. Comparison of systems top-coated with MIL-C-83286.

	Phase II System 5		Phase I System	
	MIL-P-24441 Modified		MIL-P-24441	
	Immersed		Immersed	
	No	Yes	No	Yes
Elcometer Adhesion	7.4	8.1	+	8.3
Impact, 23°C	71	49	20	32
Impact, 4°C	48	37	26	28

Figure 13. Comparison of modified and unmodified MIL-P-24441 systems.

Table 6

Gouge Resistance, Load to Penetrate (Cumulative)

System No.	Coating		To Primer (kg)	To Anodizing (kg)	Mean Coating Thickness (mils)
1	Clive Hare 9335 over Clive Hare 8799-A	Not Immersed:	4.0	5.0	6.1
		Immersed:	4.0	5.0	5.7
2	Clive Hare 9335 over Clive Hare 8799-B	Not Immersed:	3.0	6.0	4.6
		Immersed:	2.5	6.5	4.7
3	Deft MIL-C-83286 over H_2O Reducible Primer	Not Immersed:	2.0	2.0	3.1
		Immersed:	3.5	5.0	4.5
4	3M Epoxy 134	Not Immersed:	Not Penetrated at 12 kg		10.3
		Immersed:	Not Penetrated at 12 kg		12.1
5	MIL-P-24441 Modified System	Not Immersed:	6.0	7.0	5.3
		Immersed:	7.0	7.0	6.1
6	Bostik MIL-C-83286 over Bostik MIL-P-23377	Not Immersed:	1.5	3.5	1.4
		Immersed:	1.8	3.5	1.4
7	Bostik MIL-C-83286 over Bostik BMS 10-11K	Not Immersed:	2.3	2.3	3.1
		Immersed:	2.5	2.5	2.9
8	Metco 105SF with EPON 815 Sealer	Not Immersed:	Not Penetrated at 12 kg		11.8
		Immersed:	Not Penetrated at 12 kg		11.7
9	Metco 105SF with Loctite 290 Sealer	Not Immersed:	Not Penetrated at 12 kg		10.4
		Immersed:	Not Penetrated at 12 kg		11.3
10	Tufram H plus	Not Immersed:	Not Penetrated at 12 kg		0.9
		Immersed:	Not Penetrated at 12 kg		1.0
		Immersed in Otto Fuel:	Not Penetrated at 12 kg		3.0

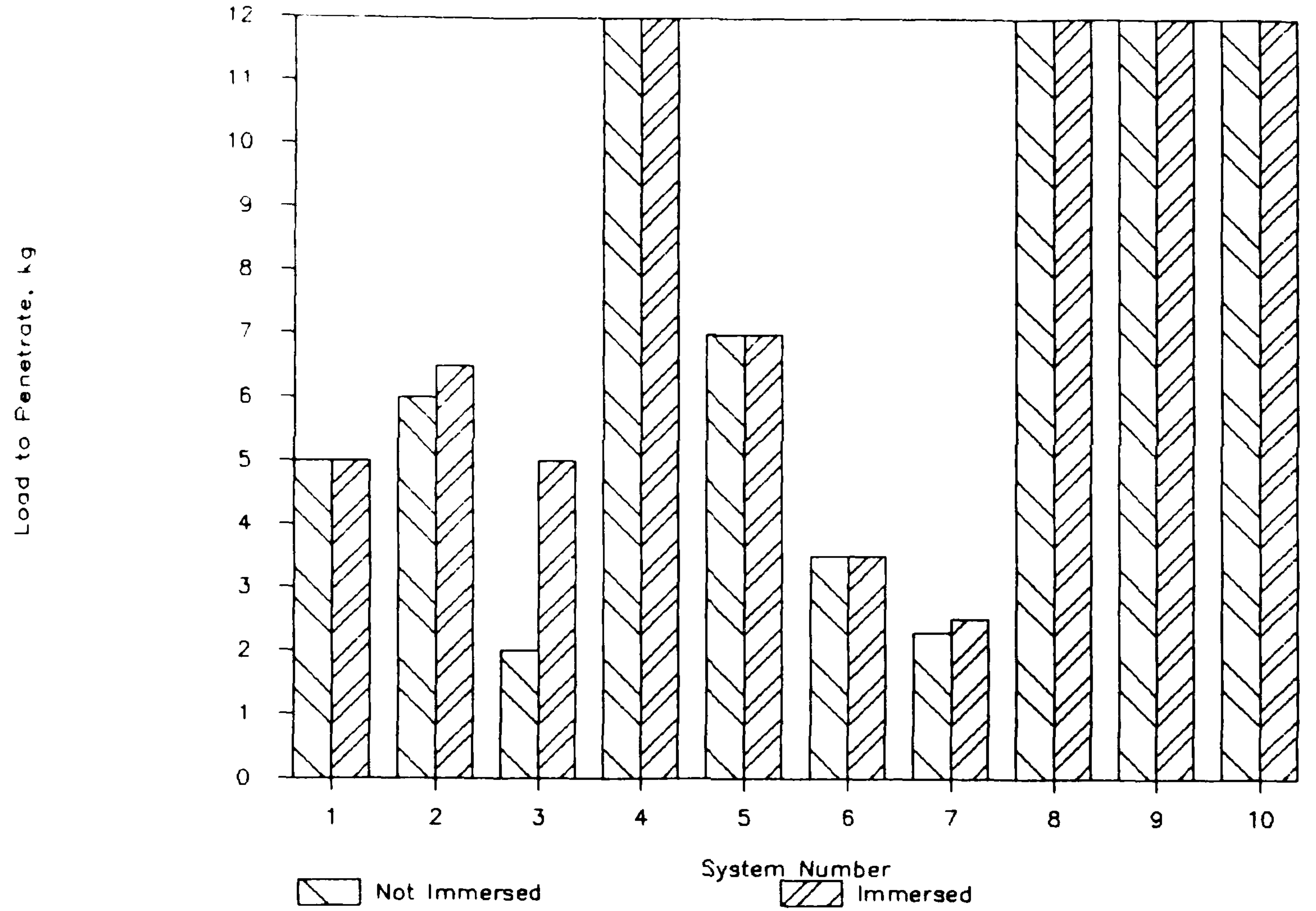


Figure 14. Gouge bar graph.

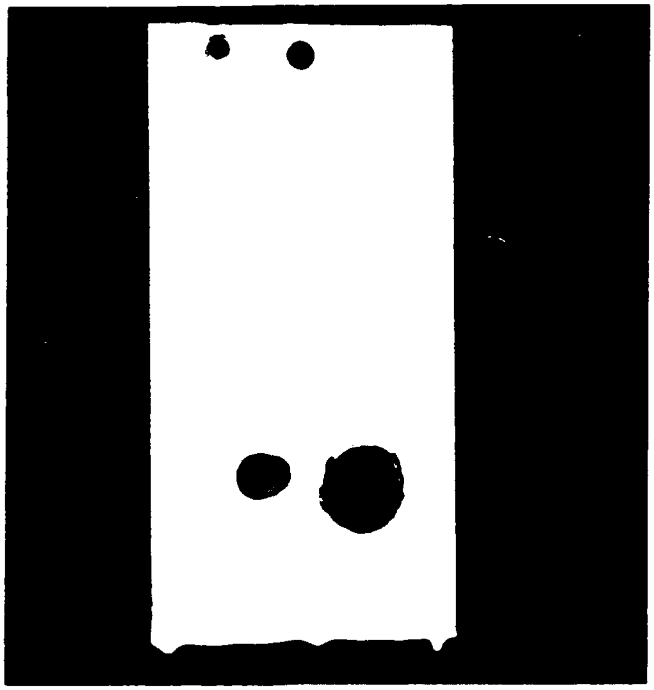


Figure 15. Corrosion at 40 in.-lb.

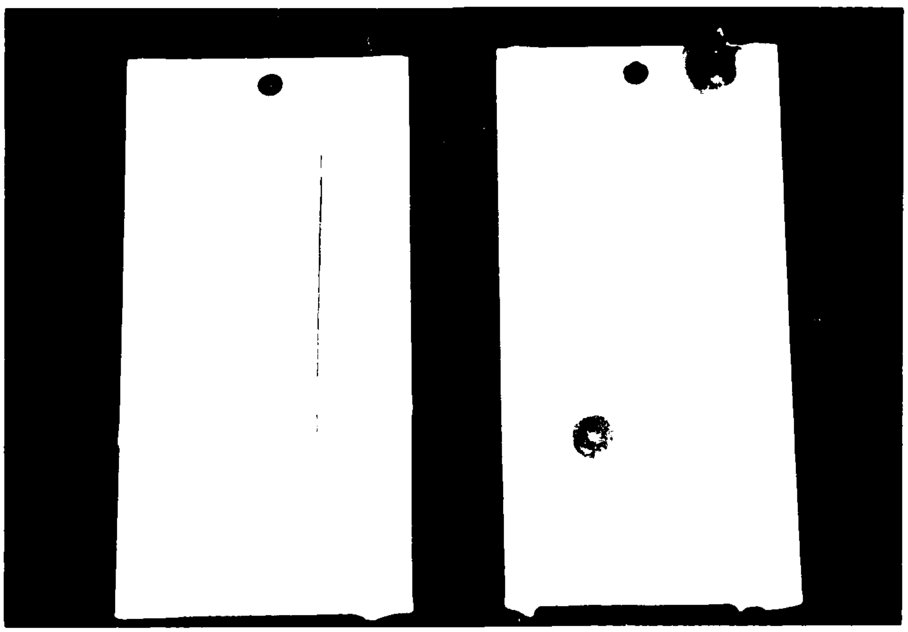


Figure 16. Immersion examples.

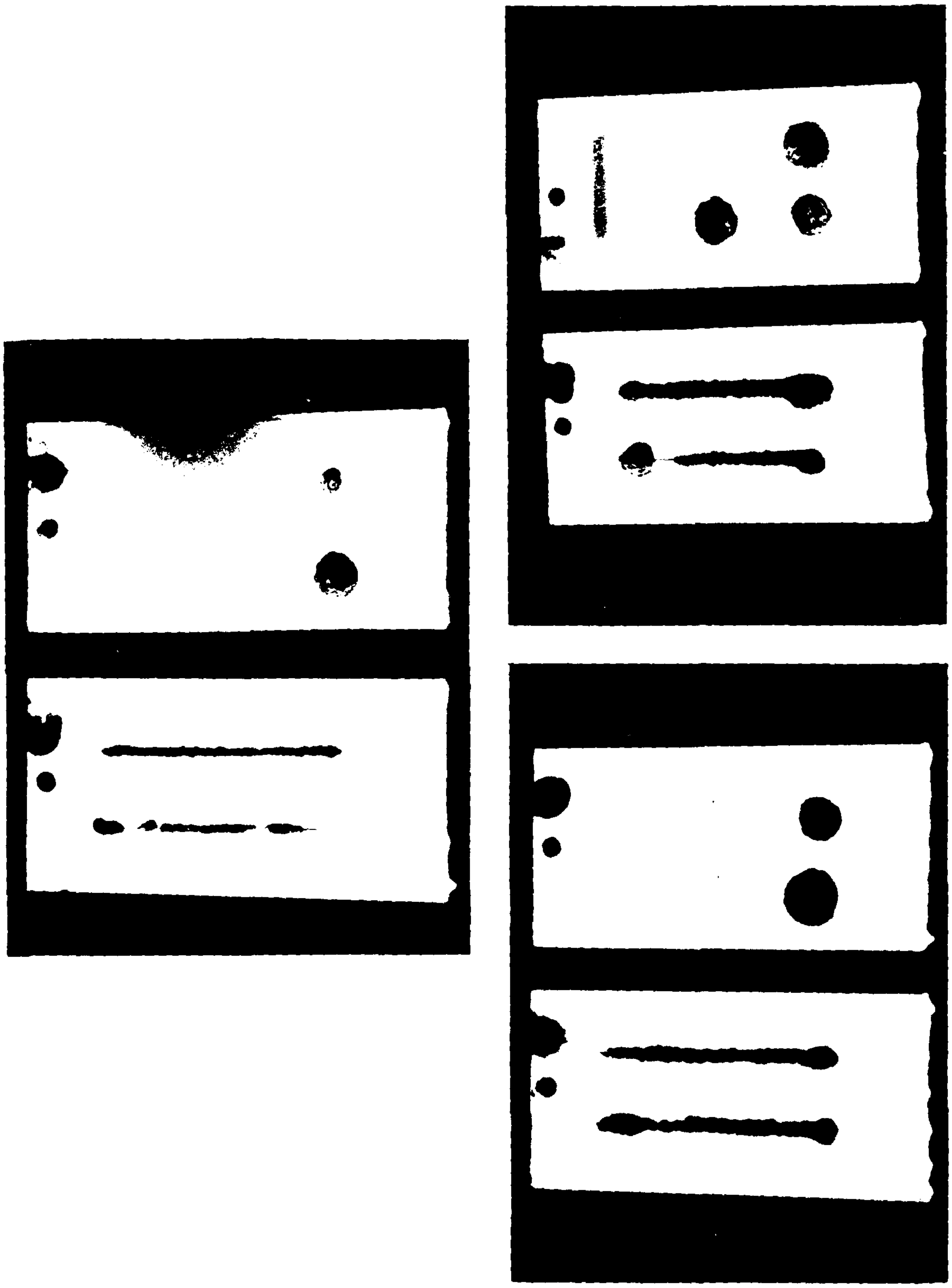


Figure 16 (Cont'd).

Table 7

Corrosion Resistance of Specimens During 90-Day Immersion

System No.	Coating	Uncoupled Undamaged	Uncoupled Scored	Uncoupled Impacted	Coupled Undamaged	Coupled Scored	Coupled Impacted
1	Clive Hare 9335 over Clive Hare 8799-A	Excellent	Excellent	Excellent	Good	Fair	Fair
2	Clive Hare 9335 over Clive Hare 8799-B	Excellent	Excellent	Excellent	Excellent	Fair	Fair
3	Deft MIL-C-83286 over H_2O Reducible Primer	Excellent	Excellent	Excellent	Fair	Poor	Poor
4	3M Epoxy 134	Excellent	Excellent	Excellent	Excellent	Poor	Poor
5	MIL-P-24441 Modified System	Excellent	Excellent	Excellent	Excellent	Fair	Poor
6	Bostik MIL-C-83286 over Bostik MIL-P-23377	Excellent	Excellent	Excellent	Poor	Poor	Poor
7	Bostik MIL-C 83286 over Bostik BMS 10-11K	Excellent	Excellent	Excellent	Poor	Fair	Fair
8	Metco 105SF with EPON 815 Sealer	Excellent	Excellent	Good	Good	Poor	Poor
9	Metco 105SF with Loctite 290 Sealer	Excellent	Excellent	Good	Poor	Poor	Poor
10	Tufram H plus	Excellent	Excellent	Excellent	Poor	Poor	Poor
	Tufram H plus (in 50/50 Otto fuel/seawater)	Good	Good	Good	Poor	Poor	Poor

Figure 17. System 1 undamaged, coupled.

Figure 18. System 2 immersion undamaged, coupled.

Figure 19. Coupled systems 3, 6, and 7.

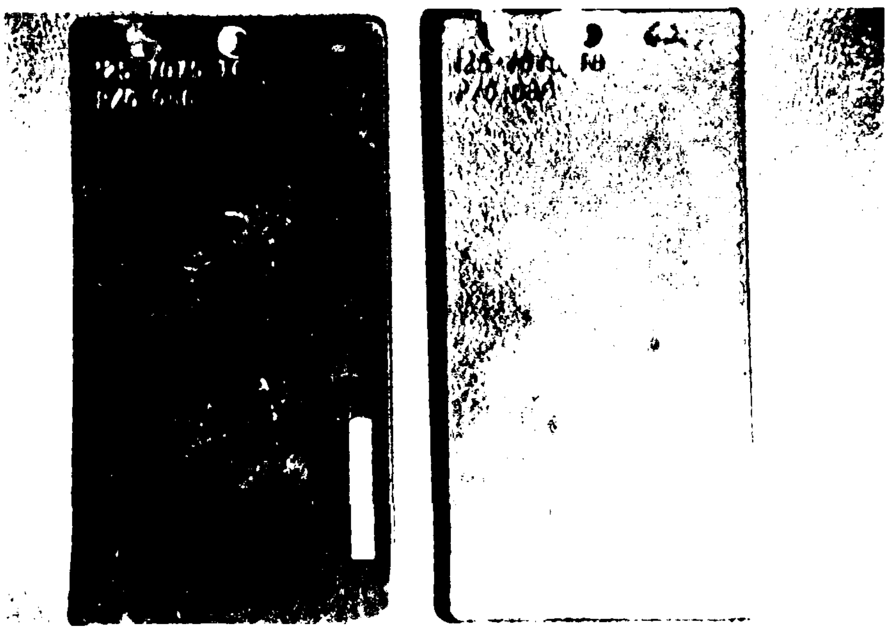


Figure 20. System 4 undamaged, coupled.

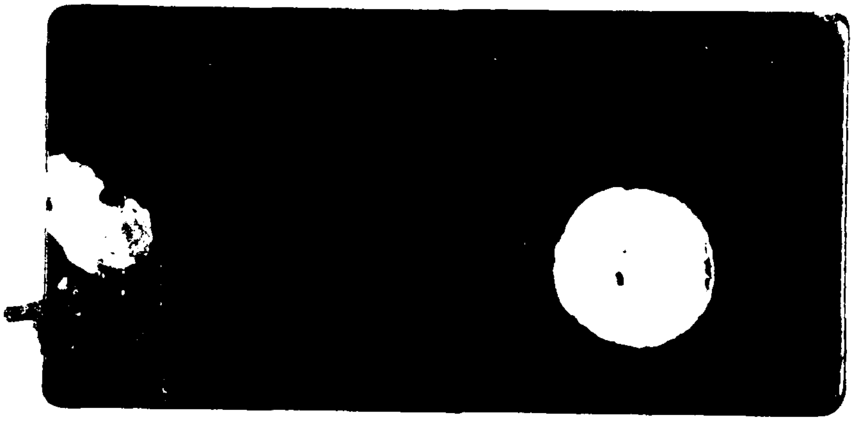


Figure 21. System 4 impacted, coupled.

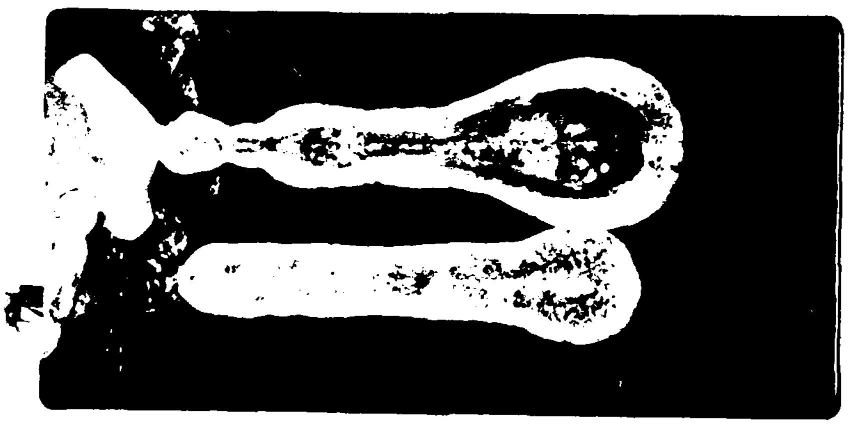


Figure 22. System 4 scored, coupled.

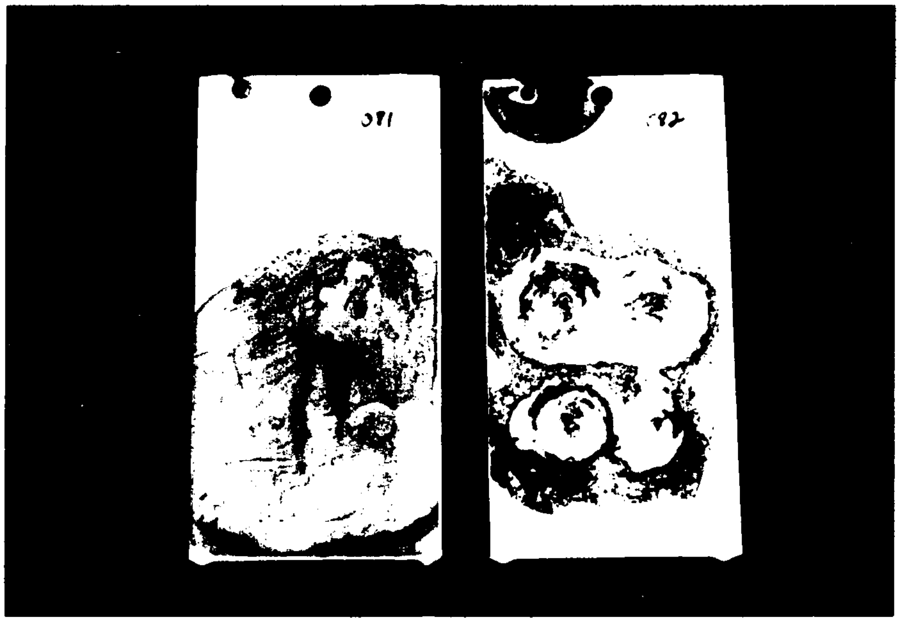


Figure 23. System 5 impacted, coupled.

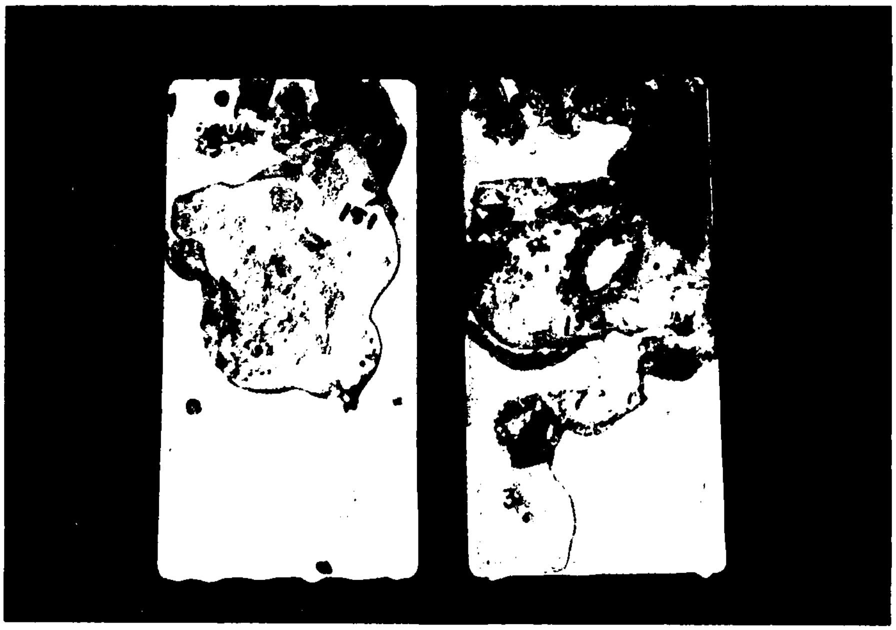


Figure 24. System 9 coupled, undamaged.

Figure 25. System 9 coupled, impacted.

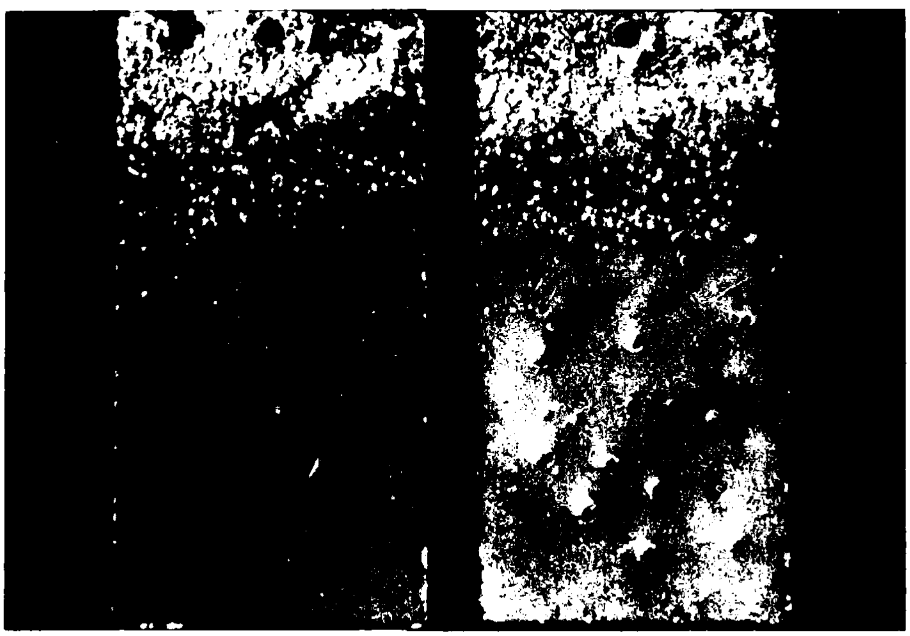


Figure 26. System 10 coupled, undamaged.

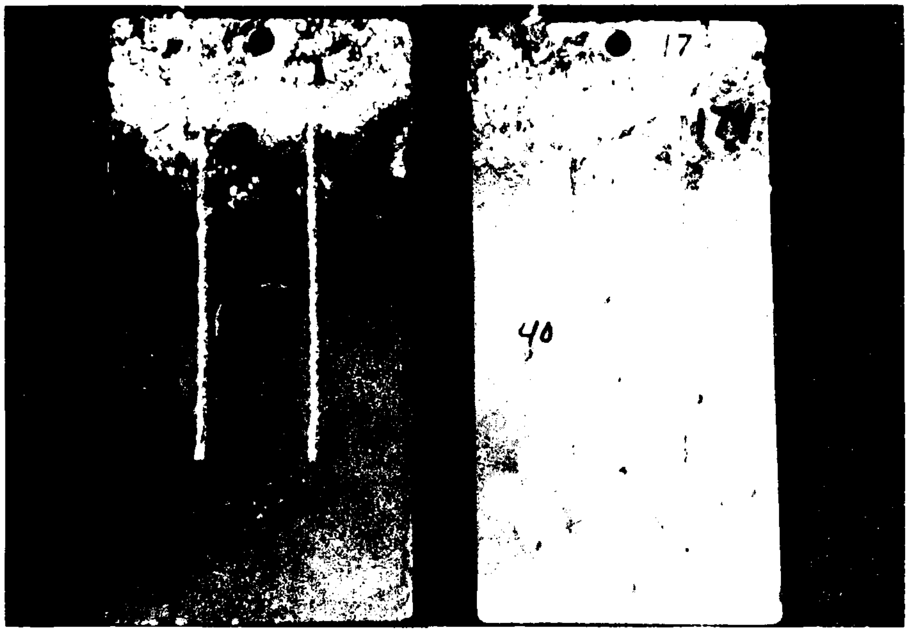


Figure 27. System 10 coupled, scored.

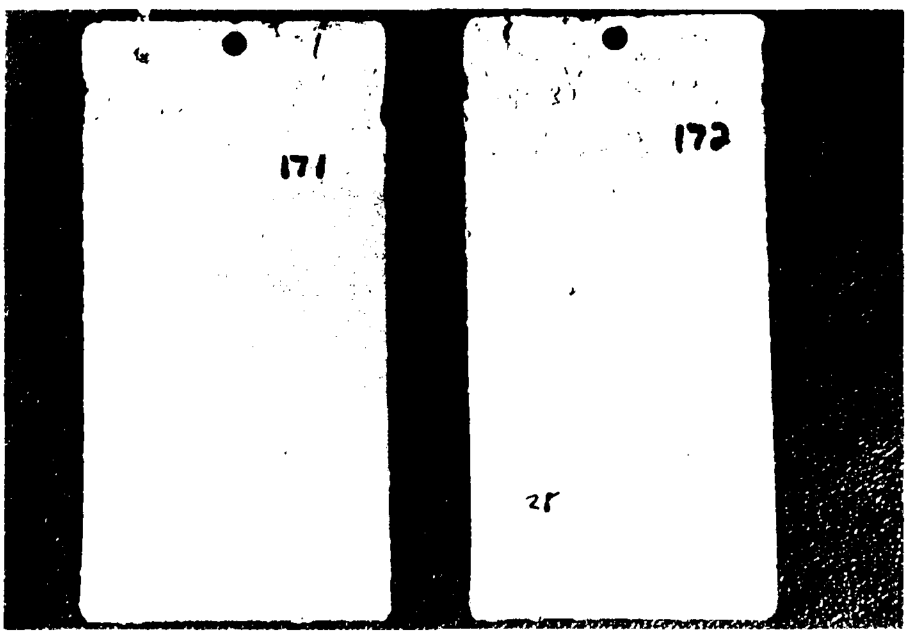


Figure 28. System 10 coupled, impacted.

Figure 29. System 10a scored.

5 RANKING OF COATINGS

Phase II Rankings

A numerical rating system was developed to compare the test results.

The coatings are ranked on a scale of 0 to 100, with 100 representing the best possible coating system that could be determined by the test methods. Appendix C provides the formulas and calculations. Figure 30 shows the rankings for the 10 systems. The following evaluation is based on this ranking.

1. Overall, 3M Epoxy 134 (System 4) is the best of the 10 coating systems evaluated. All eight physical tests were completed without failure. Its physical properties exceeded the testing limits of the impact and Elcometer Adhesion test methods. Also, the coating was not penetrated during the gouge tests at the maximum load of 12 kg. The performance of this coating system in immersion tests was excellent for specimens that were not galvanically coupled to bronze. Coupled specimens were rated fair to poor, but overall, the immersion test results were acceptable.

2. System 6 (Bostik MIL-C-83286 urethane topcoat over MIL-P-23377 epoxy primer) is rated second overall. Its performance was better than the Bostik MIL-C-83286/BMS 10-11K system (System 7) or the Deft MIL-C-83286/water-reducible epoxy primer system (System 3).

3. The MIL-P-24441 modified system (System 5) showed better impact resistance than the unmodified MIL-P-24441 system tested in Phase I. The modifications improved the impact resistance by about 130 percent at 23°C and by about 57 percent at 4°C. Elcometer Adhesion test results were slightly lower for the modified system.

4. Of the two ceramic coatings evaluated, the Metco 150SF sealed with Epon 815 (System 8) performed better than the Metco 150SF sealed with Loctite (System 9). Both coatings were chipped at low impact forces. The former system showed good resistance to corrosion in the 90-day immersion test except when damaged by impact.

5. The Clive Hare systems (Systems 1 and 2) had good resistance to corrosion in 90-day immersion, but the impact test results on these coatings were very poor.

6. System 10 (Tufram H plus) corroded very rapidly in seawater when galvanically coupled to brass. Results for a mixture of 50 percent seawater and 50 percent Otto Fuel were similar. Its use is not recommended for the MK 48 system.

Phases I and II Rankings

Table 8 lists the overall rankings of the coating systems from Phases I and II. The test methods used in Phases I and II were the same with the exception of the gouge test. Since the gouge test method used here differed significantly from the method used in Phase I, these results have not been included in determining the overall ranking. Appendix C gives the formulas for calculating the rankings.

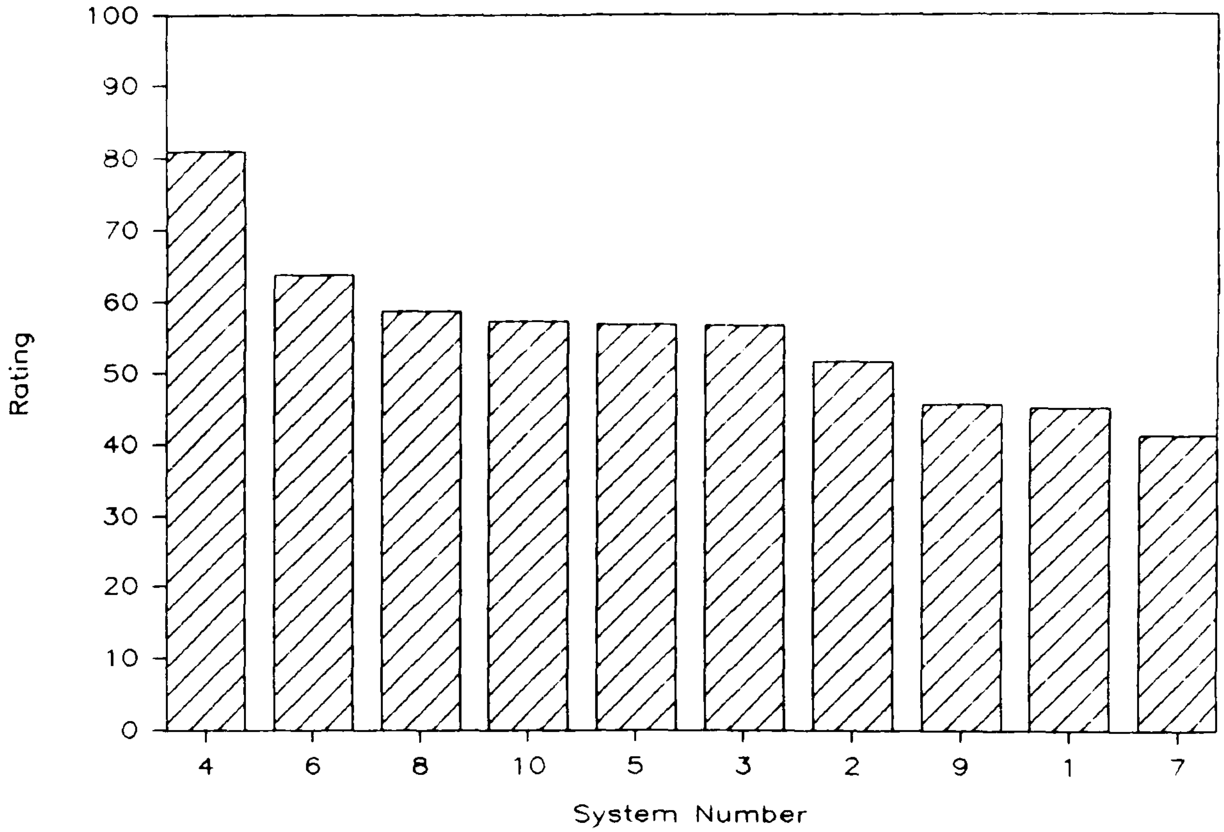


Figure 30. Final rating of 10 systems.

Figure 31 graphically displays rankings of the 20 best coating systems from Phases I and II. As shown, there are significant differences among the first four coating systems, but no major differences among the next 16. The best four coating systems are:

1. 3M Epoxy 134 applied over a chromate film on sandblasted 7075-T6 aluminum at a dry film thickness of 8 mils.

2. Bostik MIL-C-83286 nonelastomeric aliphatic urethane topcoat applied over Bostik MIL-P-23377 epoxy primer. The topcoat and the primer were each applied at a dry film thickness of 2 mils to a substrate of dichromate-sealed, hardcoat-anodized 7075-T6 aluminum.

3. Deft MIL-C-83286 nonelastomeric aliphatic urethane topcoat applied over Deft #44-GN-7 water-reducible primer. The topcoat and primer were each applied at a dry film thickness of 2 mils to dichromate-sealed, hardcoat-anodized 7075-T6 aluminum.

4. Lord Hughson elastomeric polyurethane TS 3236-23 A/B (applied at a dry film thickness of 5 mils) over MIL-P-23377 epoxy primer (applied at a dry film thickness of 1 mil) over chromate conversion-coated 7075-T6 aluminum.

Table 8

Overall Rankings of Coating Systems: Phases I and II

Phase	System Number	Sub-strate*	Primer	Topcoat	Manufacturer Primer/Topcoat	Topcoat Thickness	Final Rating
II	4	D	--	3M 134	3M	10	67
II	6	A	MIL-P-23377	MIL-C-83286	Bostik	2	60
I	42	C	MIL-P 23377	IRATHANE 155	Deft/IRATHANE	15	57
I	36	C	MIL-P-23377	L/H POLY	Deft/L Hughson	5	56
I	2	A	MIL-P-24441	MIL-P-24441	Matcote/Mobil	10	54
I	40	A	MIL-P-23377	IRATHANE 155	Deft/Irathane	15	54
I	3	A	MIL-P-24441	MIL-P 24441	Matcote/Mobil	15	53
I	5	B	MIL-P-24441	MIL-P-24441	Matcote/Mobil	10	53
I	1	A	MIL-P-24441	MIL-P-24441	Matcote/Mobil	5	52
I	4	B	MIL-P-24441	MIL-P-24441	Matcote/Mobil	5	52
II	3	A	44-GN-7	MIL-P-83286	Matcote/Mobil	4	51
I	21	A	MIL-P-23377	MIL-P-23377	Deft	15	51
I	7	C	MIL-P-24441	MIL-P-24441	Matcote/Mobil	5	51
I	9	C	MIL-P-24441	MIL-P-24441	Matcote/Mobil	15	51
I	41	B	MIL-P-23377	IRATHANE 155	Deft/Irathane	15	51
I	33	C	TS 3236-26	TS 3236-23A/B	Lord Hughson	5	50
II	5	A	MIL-P-24441**	MIL-P-24441**	USA-CERL	5	49
I	6	B	MIL-P-24441	MIL-P-24441	Matcote/Mobil	15	49
I	8	C	MIL-P-24441	MIL-P-24441	Matcote/Mobil	10	49
I	27	B	AMERCOAT 86	AMERCOAT 99	Ameron	15	49
I	17	A	MIL-P-23377	100% SOLIDS	Deft/Steelcote	10	48
I	39	C	MIL-P-23377	MIL-C=83286	Deft	5	48
I	30	C	AMERCOAT 86	AMERCOAT 99	Ameron	15	47
I	10	A	MIL-C-4556	MIL-C-4556	Plas Chem	5	46
I	11	A	MIL-C-4556	MIL-C-4556	Plas Chem	10	45
II	8	D	--	150 SF/EPON 815	Metco	12	44
II	2	A	8799B	9335	Clive Hare	5	44
I	12	A	MIL-C-4556	MIL-C-4556	Plas Chem	15	44
II	10	E	--	TUFRAM H	Gen Magnaplate	1	43
I	16	A	MIL-P-23377	100% SOLIDS	Deft/Steelcote	5	42
I	20	A	MIL-P-23377	MIL-P-23377	Deft/Steelcote	10	42
II	1	A	8799A	9335	Clive Hare	6	39
II	7	A	BMS 10-11K	MIL-C-83286	Bostik Hare	2	39
I	24	A	AMERCOAT 86	AMERCOAT 99	Ameron	15	39
I	34	A	MIL-P-23377	L/H POLY	Deft/L Hughson	5	39
I	26	B	AMERCOAT 86	AMERCOAT 99	Ameron	10	39
I	29	C	AMERCOAT 86	AMERCOAT 99	Ameron	10	38
I	18	A	MIL-P-23377	100% SOLIDS	Deft/Steelcote	15	37
I	35	B	MIL-P-23377	L/H POLY	Deft/L Hughson	5	35
I	13	A	MIL-P-23377	MIL-C-22750	Deft/Chemrex	5	35
II	19	A	MIL-P-23377	MIL-P-23377	Deft	5	35
I	28	C	AMERCOAT 86	AMERCOAT 99	Ameron	5	35
I	23	A	AMERCOAT 86	AMERCOAT 99	Ameron	10	34
I	31	A	TS 3236-26	TS 3236-23A/B	Lord Hughson	5	34
I	22	A	AMERCOAT 86	AMERCOAT 99	Ameron	5	34
I	25	B	AMERCOAT 86	AMERCOAT 99	Ameron	5	34
I	32	B	TS 3236-26	TS 3236-23A/B	Lord Hughson	5	33
II	9	D	--	150 SF/LOC 2909	Metco	12	31
I	38	B	MIL-P-23377	MIL-C-83286	Deft	5	28
I	15	A	MIL-P-23377	MIL-C-22750	Deft/Chemrex	15	28
I	37	A	MIL-P-23377	MIL-C-83286	Deft	5	27
I	14	A	MIL-P-23377	MIL-C-22750	Deft/Chemrex	10	27

*A 7075 T6 Aluminum alloy, sandblasted, hardcoat anodized, and dichromate-sealed.
B 7075-T6 Aluminum alloy, sandblasted, hardcoat-anodized.
C 7075-T6 T6 Aluminum alloy, sandblasted, chromate conversion-coated.
D 7075 T6 Aluminum alloy, sandblasted.
E 7075-T6 Aluminum alloy, smooth.
**Modified formula.

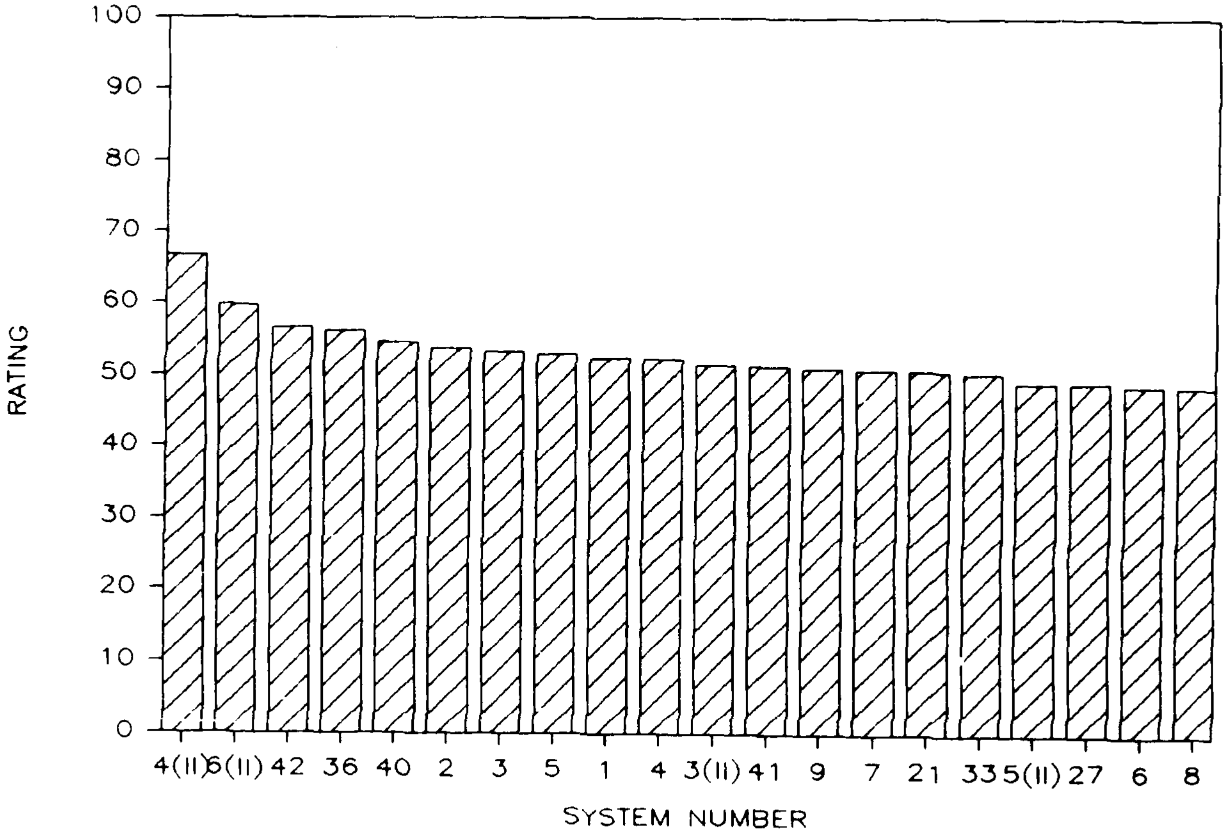


Figure 31. Top 20 coating systems.

6 SUMMARY

This report has documented the second phase of research conducted to find the best protective coating system for the Navy's MK 48 Torpedo. Ten coating systems were tested for adhesion and their resistance to impact, gouging, and corrosion. The systems were then ranked according to their performance. Final rankings included the systems tested during Phase I of the research.

The best system was found to be 3M Epoxy 134. Second, third, and fourth, respectively, were Bostik MIL-C-83286, Deft MIL-C-83286, and Lord Hughson elastomeric polyethylene TS 3236-23 A/B.

7 RECOMMENDATIONS

Two recommendations are made to improve future test procedures:

1. The Elcometer Adhesion test has been performed using a hand-held test unit. The unit is well-adapted to field use, but more accurate results may be obtained in a laboratory setting using a tensile-testing machine.

2. The upper limit of the Elcometer Adhesion test is about 900 psi--the strength of the epoxy adhesive used to bond the aluminum dolly to the coating surface. A better adhesive (or bonding method) that could extend the limit to 2000 psi or more would reduce the number of "glue failures" and allow more meaningful results to be obtained.

8 DISCUSSION

Based on results of USA-CERL Phases I and II and other NUSC laboratory and *in-situ* testing, a USA-CERL Phase III testing effort will be conducted to explore, in more detail, the optimum protective coating system selection for the MK 48 Torpedos. In Phase III, surface preparation will be rigorously defined; specific effects of anodizing and sandblasting will be explored in detail. Many protective coating systems, including numerous powder epoxies on anodized aluminum, will be tested in this next phase of research.

METRIC CONVERSIONS

1 mil	=	0.0254 mm
1 in.	=	25.4 mm
1 psi	=	6.89 kPa
1 in.-lb	=	1.1298×10^6 dyne centimeters
1 lb	=	0.453 kg
1 lb/sq in.	=	703.070 kg/m^2
1 oz	=	28.3495 g
1 fl oz	=	29.5735 cm^3
(°F-32) x 0.55	=	°C

APPENDIX A:

FORMULATIONS FOR MIL-P-24441 MODIFIED WITH KELPOXY G293-100

MIL-P-24441 Formula 158 Component B Modified

Ingredient	Relative Weight
Thixatrol ST (1)*	15
Epon 815 (2)	400
Kelpoxy G293-100 (3)	120
Pfizer Talc Cp20-30 (4)	50
Celite 499 (5)	120
Imperial Strontium Chromate (6)	100
Amsco Super High Flash Naptha (7)	270

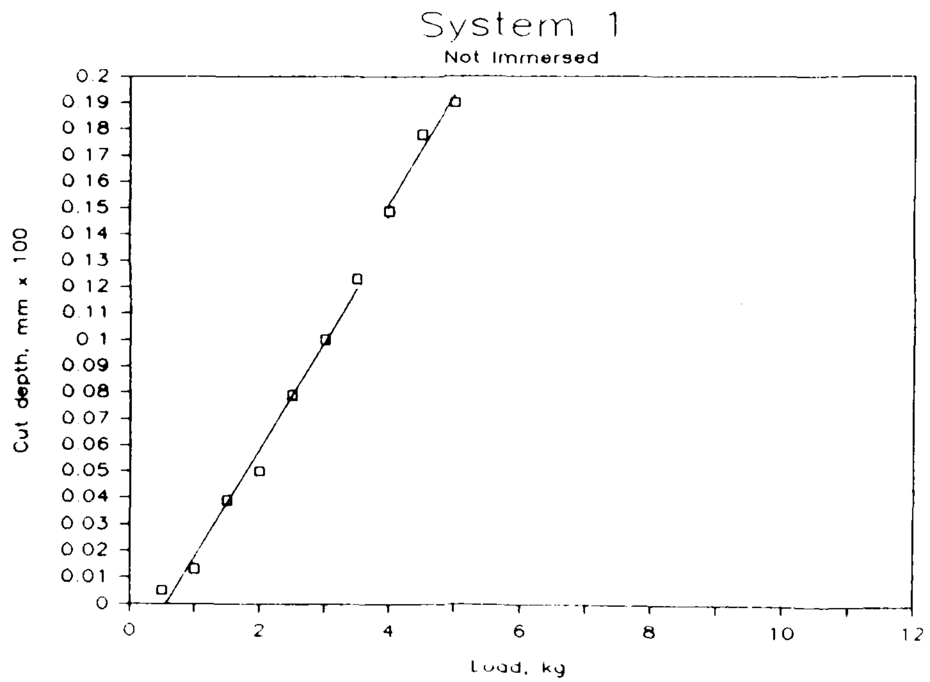
MIL-P-24441 Formula 152 Component B Modified

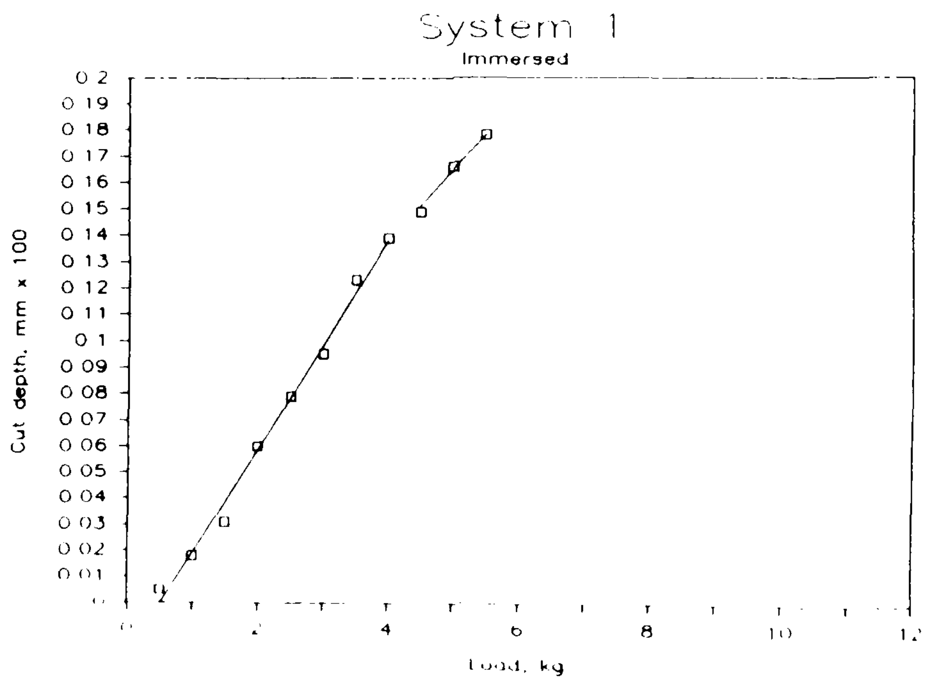
Ingredient	Relative Weight
Thixatrol ST	10
Epon 815	400
Kelpoxy G293-100	120
Pfizer Talc CP20-30	250
Amsco Super High Flash Naptha	251

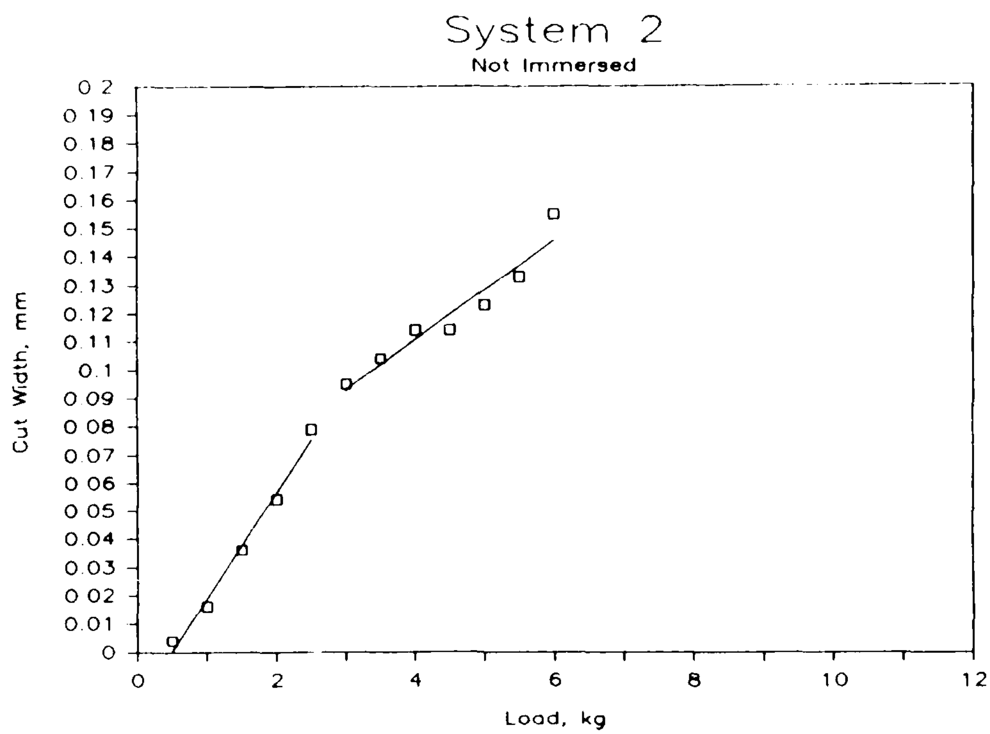
*Numbers in parentheses refer to the following manufacturers: (1) N. L. Industries; (2) Shell Chemical Co.; (3) Spencer-Kellogg; (4) Pfizer Minerals and Pigments Division; (5) Johns-Manville; (6) Imperial Paper and Color Corporation; and (7) Union Chemicals Division, Union Oil Co. of California.

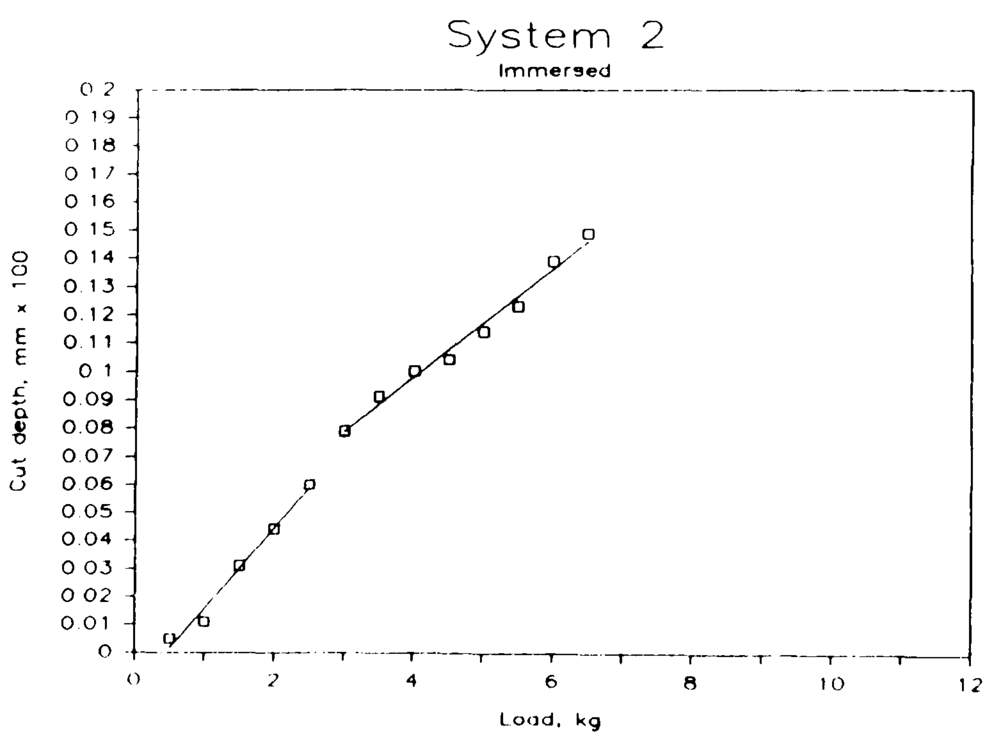
APPENDIX B:

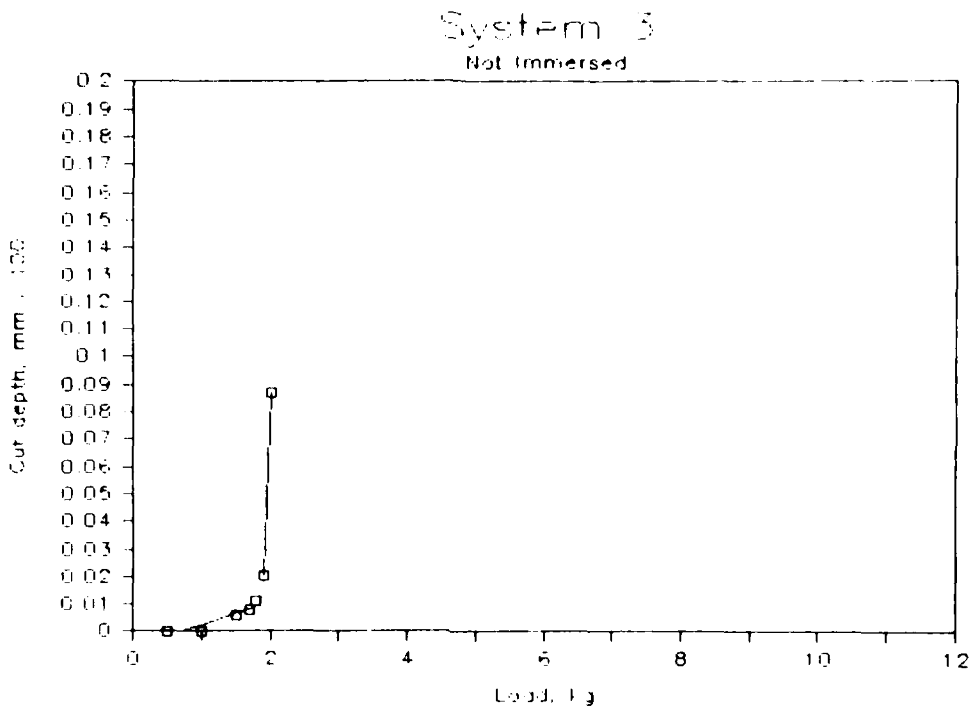
GOUGE TEST RESULTS



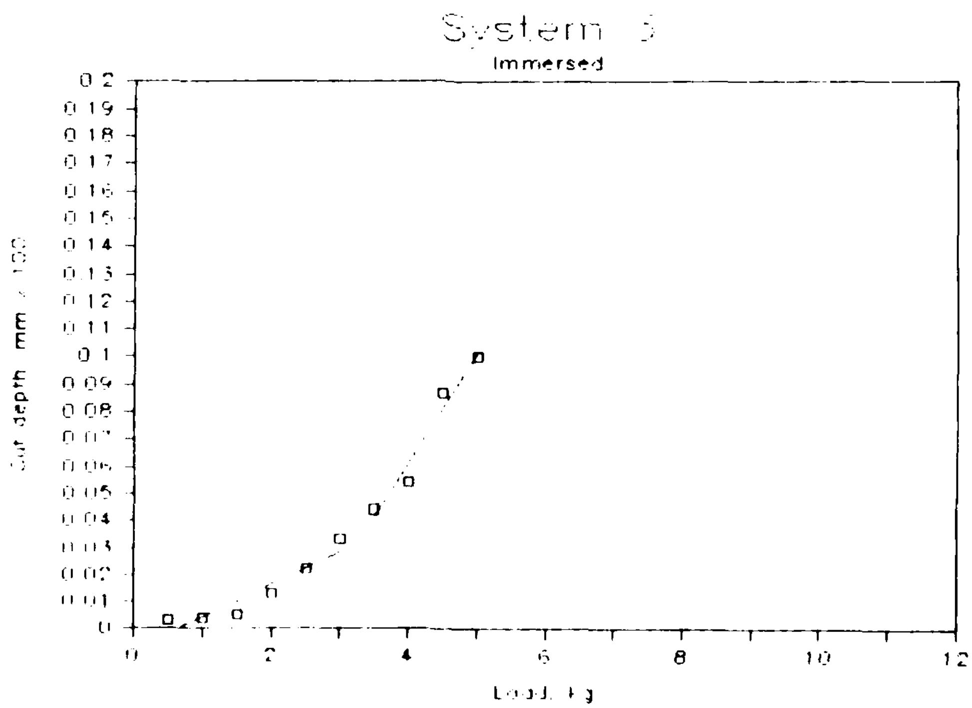



System 2
Not Immersed
Cut Width, mm
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
Load, kg

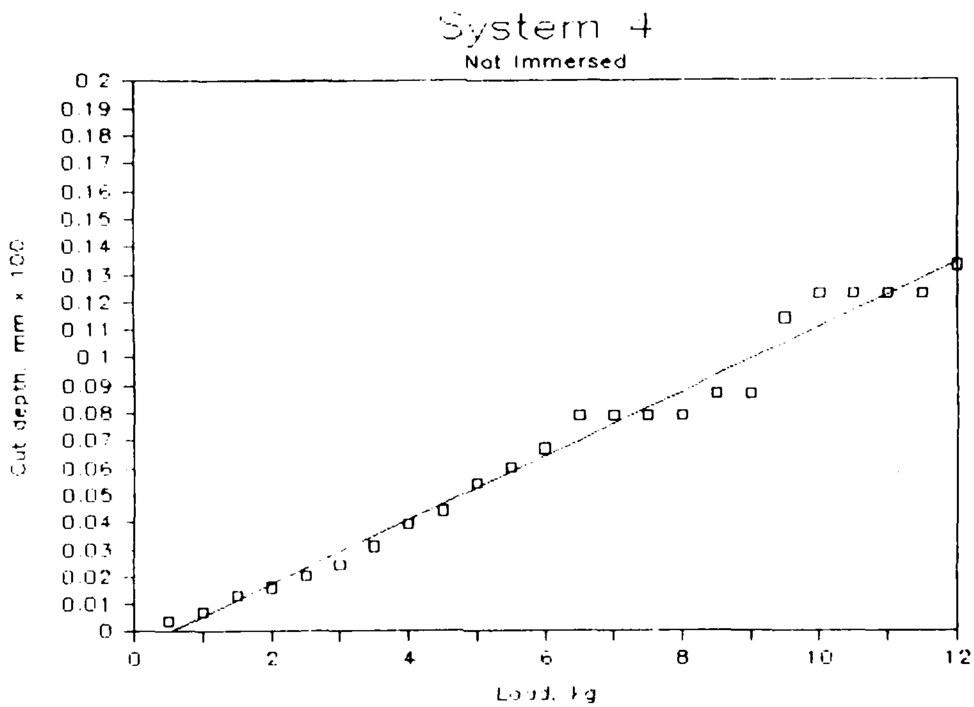

System 2
Immersed
Cut depth, mm x 100
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12
Load, kg

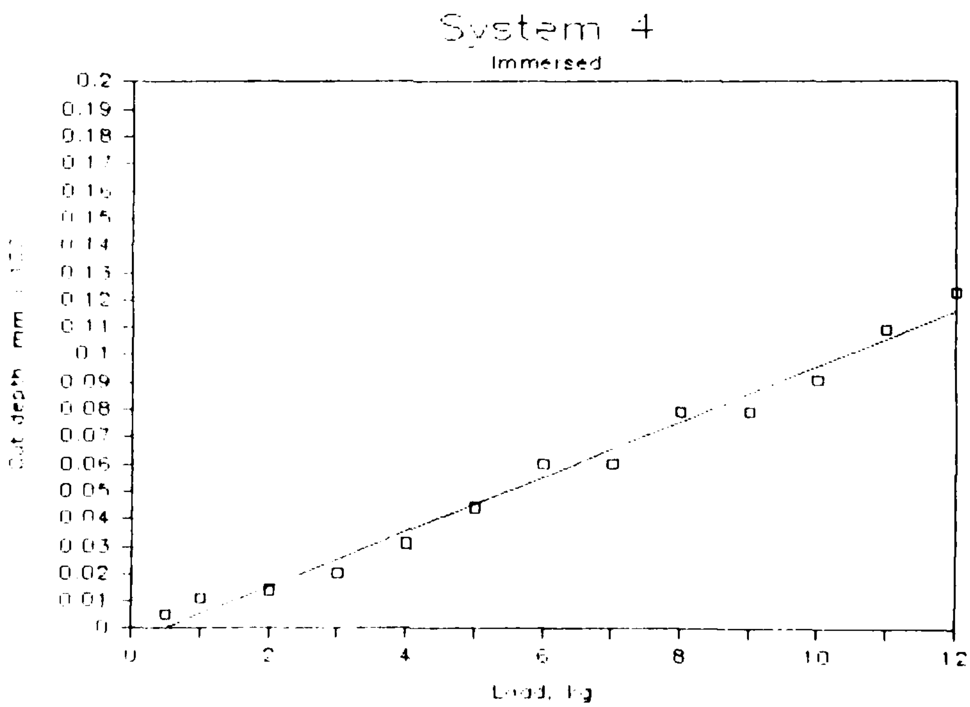


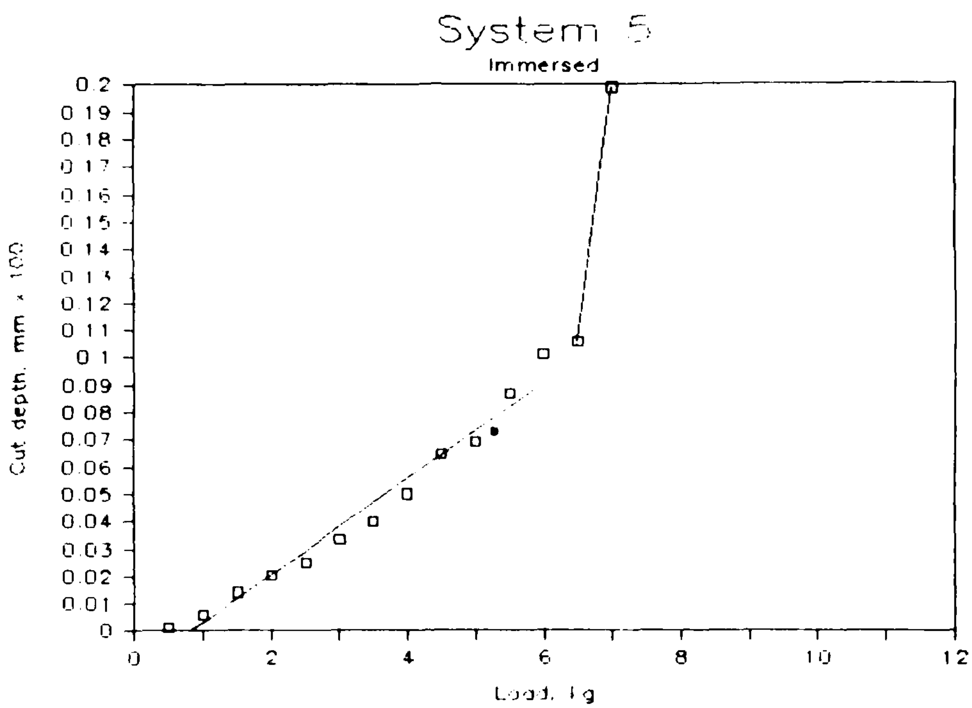
System 3
Not Immersed
Cut depth, mm × 100
Load, kg

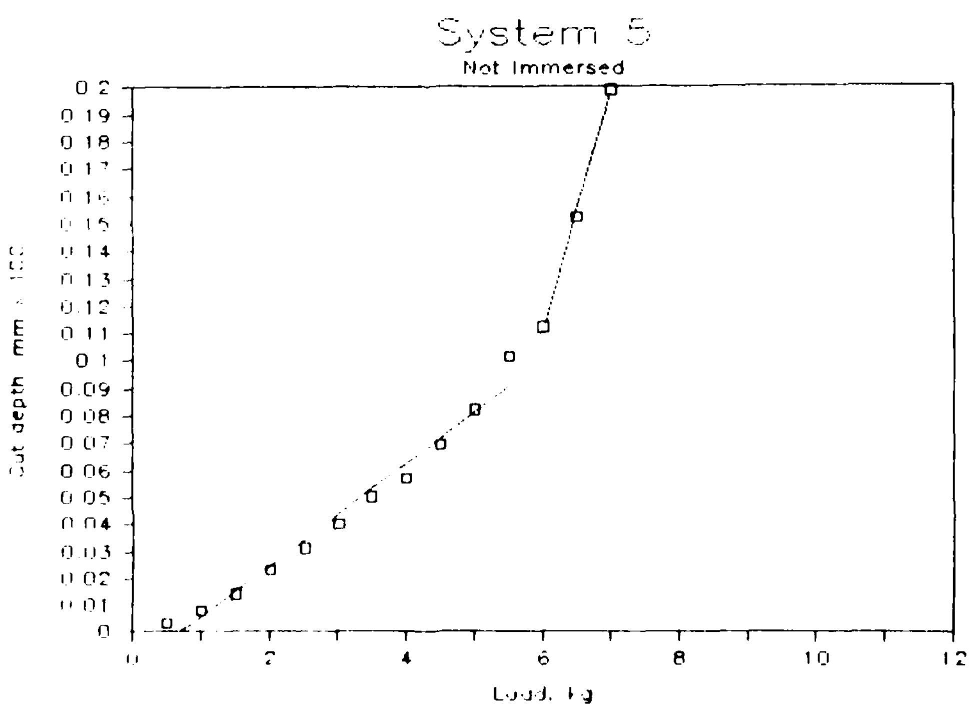


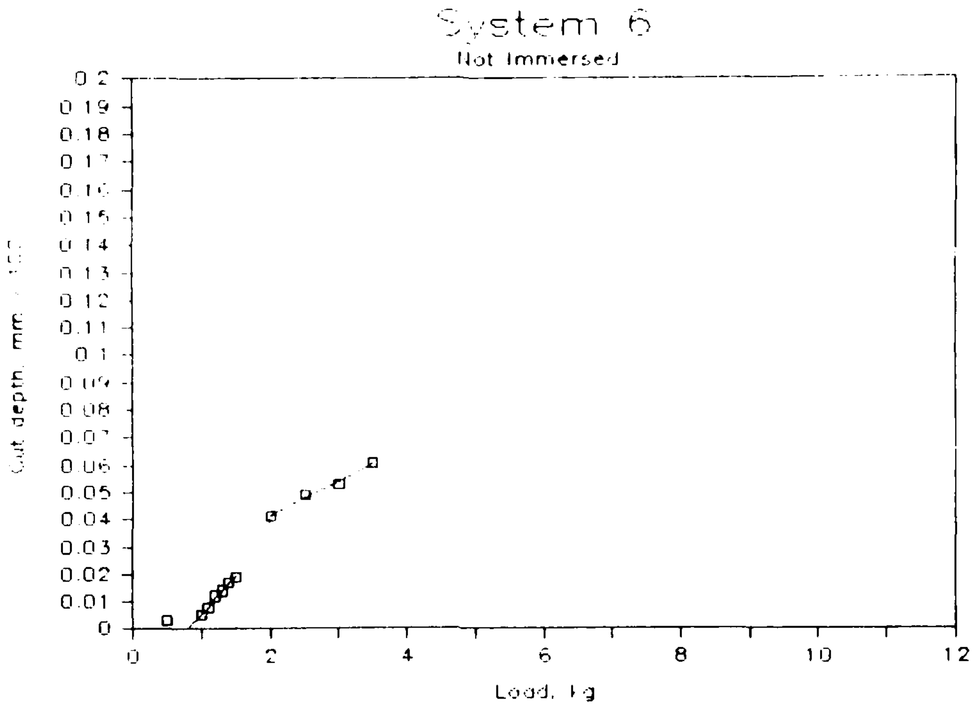
System 3
Immersed
Cut depth, mm × 100
Load, kg

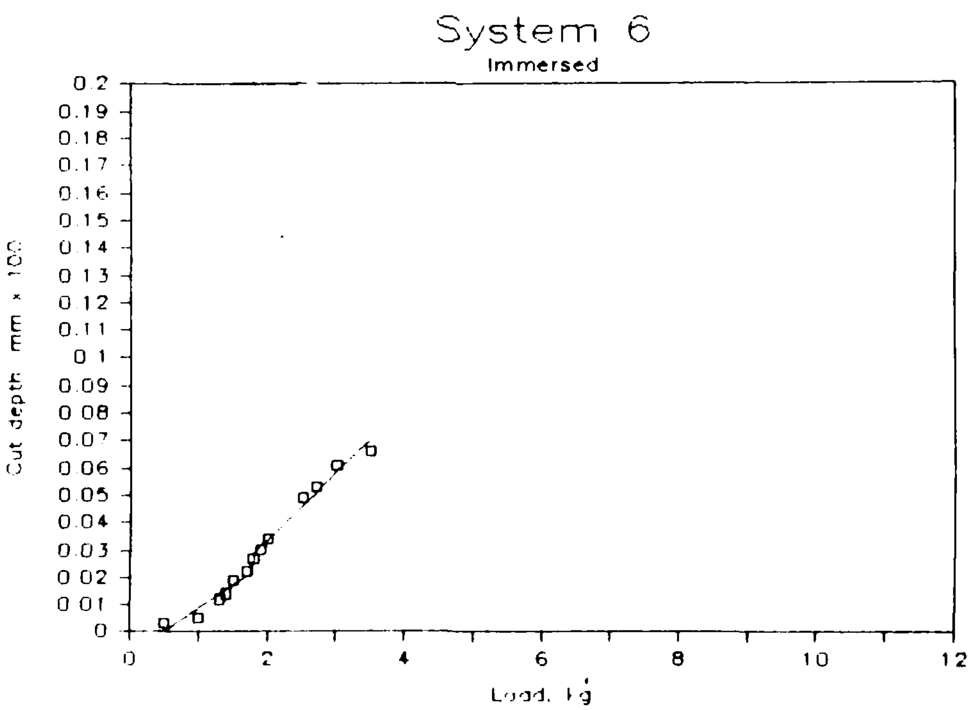

System 4
Not Immersed
Cut depth, mm × 100
Load, kg

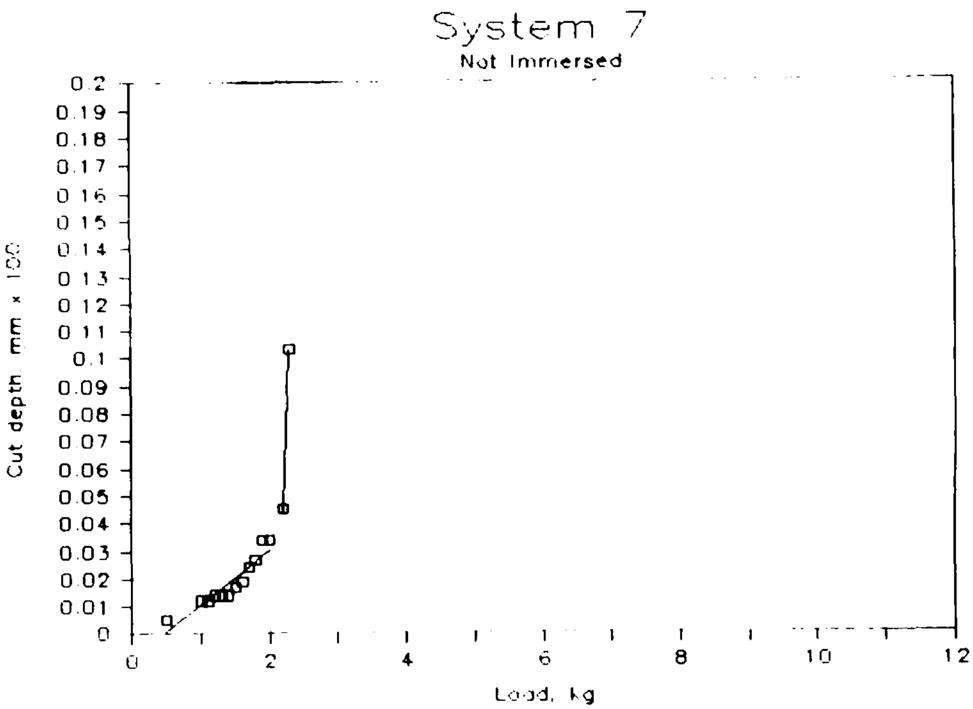

System 4
Immersed
Load, kg

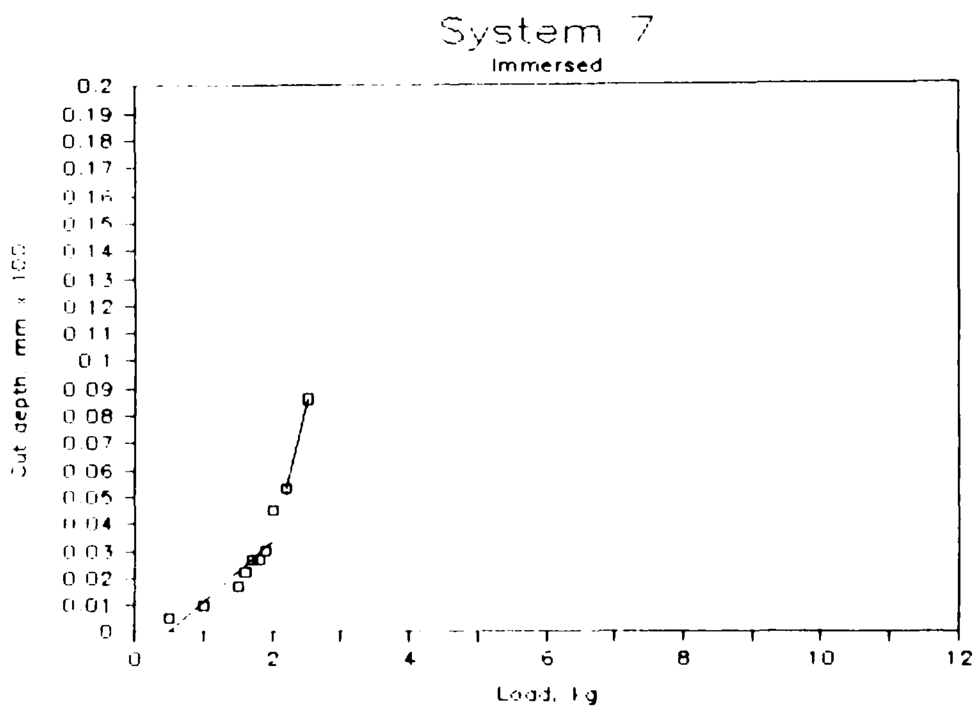

System 5
Immersed
Cut depth, mm × 100
Load, kg
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0
2
4
6
8
10
12

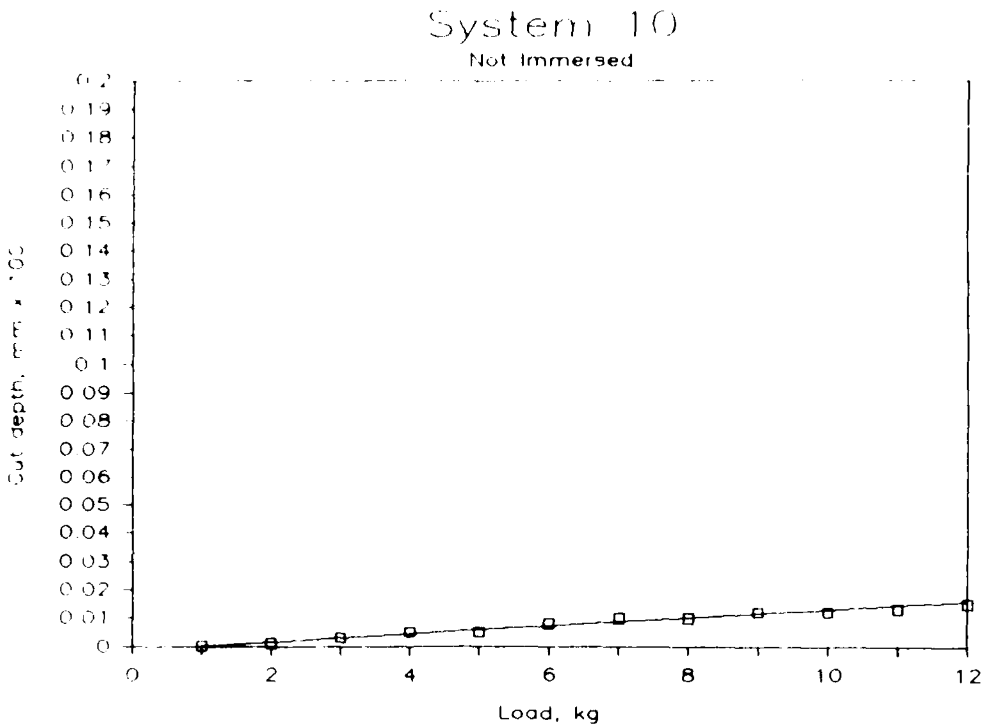

System 5
Not Immersed
Cut depth, mm × 100
Load, kg
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0
2
4
6
8
10
12

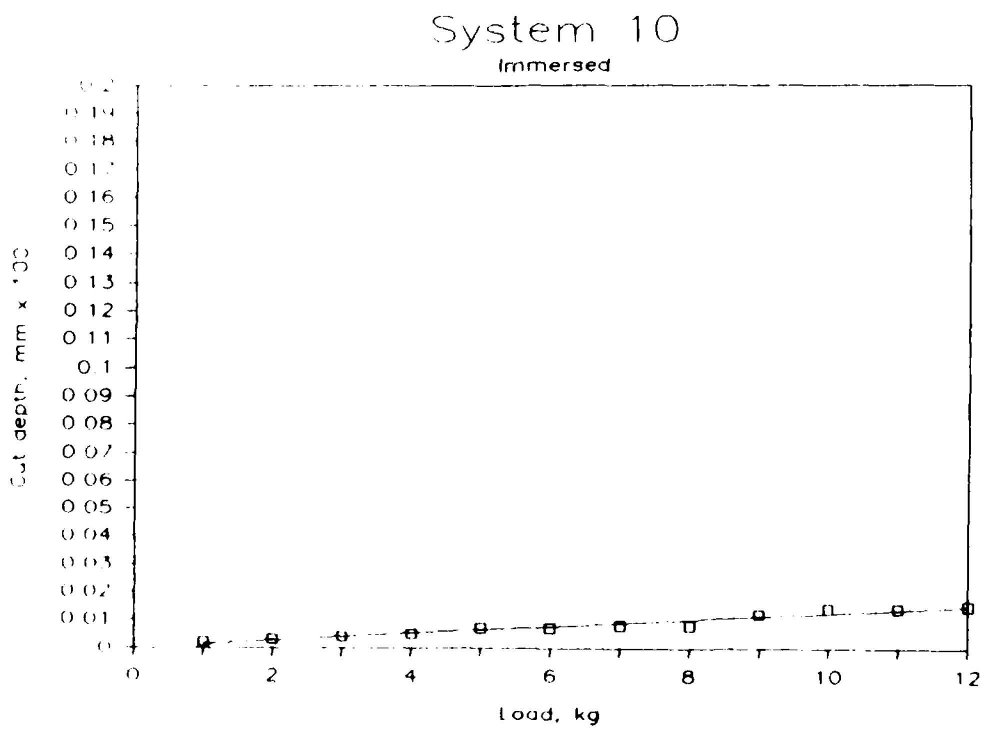

System 6
Not Immersed
Cut depth, mm
Load, kg

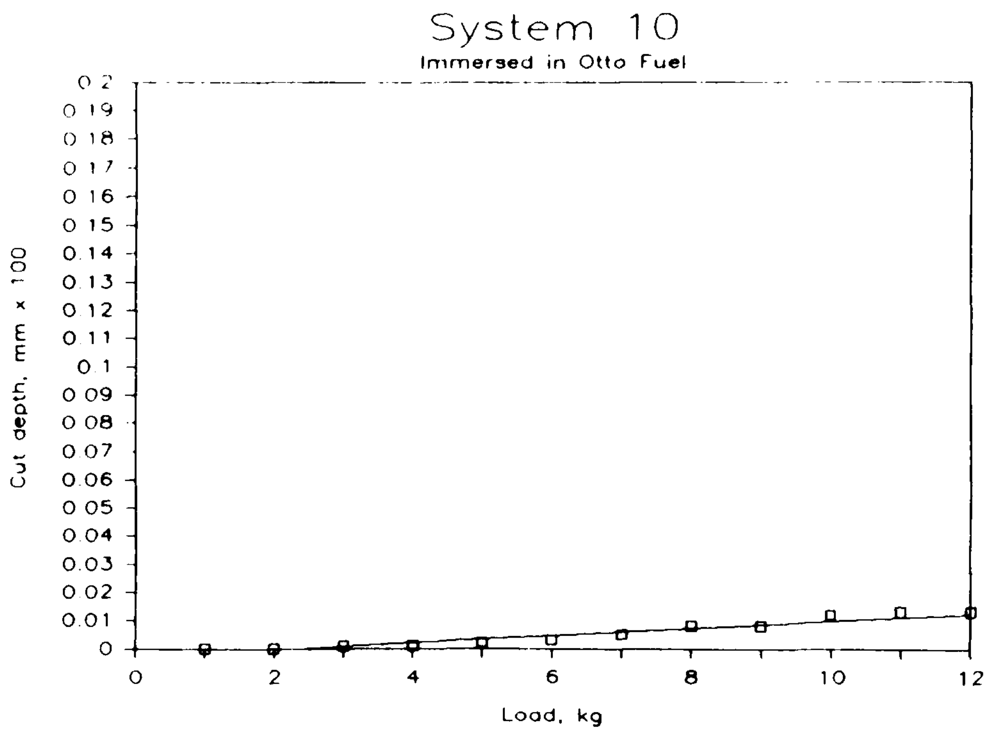

System 6
Immersed
Cut depth, mm x 100
Load, kg


System 7
Not Immersed
Cut depth mm × 100
Load, kg


System 7
Immersed
Cut depth mm × 100
Load, kg


System 10
Not Immersed
Cut depth, mm x 100
Load, kg


System 10
Immersed
Cut depth, mm x 100
Load, kg


System 10
Immersed in Otto Fuel
Cut depth, mm x 100
Load, kg
0.2
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
2
4
6
8
10
12

APPENDIX C:

COATING RANKING FORMULAS AND CALCULATIONS

The rating system set forth here was developed according to criteria suggested by NUSC. All tests results were considered to contribute equally to the protection of the torpedo in service, and thus were given equal weight in the calculation of the numerical ratings. The rating system is constructed as follows:

First, the test data were entered in columns 2 through 15 (of Table C1). The physical test data, columns 2 through 9, are taken directly from Table 5. The immersion entered in columns 10 through 15 are derived from test data given in Table 7. Word label ratings were converted into numerical ratings as follows:

Poor	=	0
Fair	=	1
Good	=	2
Excellent	=	3

Second, scaling factors were entered in row 1. Each scaling factor represents the maximum possible score for the test method as used in this study. The final ratings were calculated by dividing each data point by its scaling factor, summing these across the row, and dividing the result by a normalization factor to adjust the results to a scale of 0 to 100, where 100 represents the best possible coating as determined by these test methods.

Table C2 calculates the combined cumulative ratings of Phases I and II. The calculation method is the same. However, the gouge test result is not included because the test methods used in Phases I and II were substantially different.

Table C1

Spreadsheet for Calculating Final Ratings

System No.		Not Immersed				Immersed				Uncoupled			Coupled			Final Rating
		Elco	Imp 23° C	Imp 4° C	Gouge	Elco	Imp 23° C	Imp 4° C	Gouge	Undam	Serp	Impt	Undam	Serp	Impt	
	Scale:	10	210	210	12	10	210	210	12	3	3	3	3	3	3	
1		5.6	6	9	5.0	4.5	6	8	5.0	3	3	3	2	1	1	45
2		7.8	7	7	6.0	6.5	6	4	6.0	3	3	3	3	1	1	52
3		1.9	210	122	2.0	8.5	174	85	7.0	3	3	3	1	0	0	57
4		10.0	210	210	12.0	10.0	210	210	12.0	3	3	3	1	0	0	81
5		7.4	71	48	7.0	8.1	49	37	6.0	3	3	3	3	1	0	57
6		10.0	194	186	3.5	10.0	173	151	3.5	3	3	3	0	0	0	64
7		4.1	81	63	2.3	4.1	37	19	1.9	3	3	3	0	1	1	41
8		10.0	31	24	12.0	10.0	32	30	12.0	3	3	2	0	0	0	59
9		4.8	31	23	12.0	6.6	35	32	12.0	3	3	3	0	0	0	46
10		10.0	84	56	12.0	10.0	34	39	12.0	3	3	3	0	0	0	56

Table C2

Cumulative Ratings--Phases I and II

Phase No.	System No.	Thickness/ Substrate	Not Immersed Elco	Not Immersed Imp 23° C	Not Immersed Imp 4° C	Immersed Elco	Immersed Imp 23° C	Immersed Imp 4° C	Uncoupled Undam	Uncoupled Scr	Uncoupled Impt	Coupled Undam	Coupled Scr	Coupled Impt	Final Rating
		Scale:	10	210	210	10	210	210	3	3	3	3	3	3	
II	1(II)	6/A	5.6	6	9	4.5	6	8	3	3	3	2	1	1	39
II	2(II)	5/A	7.8	7	7	6.5	6	4	3	3	3	3	1	1	44
II	3(II)	4/A	1.9	210	122	8.5	174	85	3	3	3	1	0	0	51
II	4(II)	10/D	10.0	210	210	10.0	210	210	3	3	3	1	0	0	67
II	5(II)	5/A	7.4	71	48	8.1	49	37	3	3	3	3	1	0	49
II	6(II)	2/A	10.0	194	186	10.0	173	151	3	3	3	0	0	0	60
II	7(II)	2/A	4.1	81	63	4.1	37	19	3	3	3	0	1	1	39
II	8(II)	12/D	10.0	31	24	10.0	32	30	3	3	2	3	0	0	44
II	9(II)	12/D	4.8	31	23	6.0	35	32	3	3	2	0	0	0	31
II	10(II)	1/E	10.0	84	56	10.0	34	39	3	3	3	0	0	0	43
I	1	5/A	10.0	20	26	8.3	32	28	3	3	3	3	2	1	52
I	2	10/A	10.0	24	28	10.0	33	23	3	3	3	3	2	1	54
I	3	15/A	10.0	22	22	10.0	26	23	3	3	3	3	2	1	53
I	4	5/B	10.0	28	28	7.7	30	27	3	3	3	3	2	1	52
I	5	10/B	10.0	34	26	8.5	29	25	3	3	3	2	2	2	53
I	6	15/B	10.0	26	20	10.0	31	22	3	3	3	3	0	1	49
I	7	5/C	10.0	24	20	10.0	21	24	2	3	3	3	2	1	51
I	8	10/C	10.0	22	28	10.0	25	21	3	3	3	3	1	0	49
I	9	15/C	10.0	26	22	10.0	27	19	3	3	3	3	2	0	51
I	10	5/A	5.5	24	58	6.6	21	27	3	3	2	3	1	2	46
I	11	10/A	6.4	24	24	7.2	27	39	3	3	2	2	1	2	45
I	12	15/A	4.1	34	30	5.5	11	29	3	3	2	3	1	2	44
I	13	5/A	2.5	6	8	1.7	16	10	3	3	2	3	1	1	35
I	14	10/A	1.5	20	10	1.4	7	8	2	3	2	3	0	0	27
I	15	15/A	0.3	18	12	0.5	9	8	2	3	2	3	0	1	28
I	16	5/A	10.0	10	4	7.3	5	4	3	3	2	2	1	1	42
I	17	10/A	10.0	4	6	9.0	4	4	3	3	2	3	1	2	48
I	18	15/A	5.5	20	14	6.9	8	8	3	3	2	1	1	1	37
I	19	5/A	1.0	10	6	2.9	10	8	1	3	2	3	2	2	35
I	20	10/A	5.3	6	14	8.2	10	11	1	3	2	3	2	2	42
I	21	15/A	10.0	26	12	10.0	18	32	2	3	2	3	2	2	51
I	22	5/A	2.6	12	14	2.3	14	13	3	3	2	2	1	1	34
I	23	10/A	2.2	14	18	1.8	15	19	3	3	2	2	1	1	34
I	24	15/A	2.4	32	30	2.3	29	33	3	3	2	2	1	2	39
I	25	5/B	2.2	12	14	2.2	10	20	3	3	3	1	2	0	34
I	26	10/B	2.5	16	22	2.0	19	29	3	3	3	2	2	1	39
I	27	15/B	2.4	34	48	4.9	32	52	3	3	3	3	2	2	49
I	28	5/C	3.1	12	24	2.3	13	40	3	3	3	1	2	0	35

Table C2 (Cont'd)

Phase No.	System No.	Thickness/ Substrate	Not Immersed			Immersed			Uncoupled			Coupled			
			Elco	Imp 23° C	Imp 4° C	Elco	Imp 23° C	Imp 4° C	Undam	Scr	Impt	Undam	Scr	Impt	Final Rating
		Scale:	10	210	210	10	210	210	3	3	3	3	3	3	
I	29	10/C	3.0	20	36	1.8	20	33	3	3	3	2	2	0	38
I	30	15/C	1.6	38	58	2.0	41	55	3	3	3	3	2	2	47
I	31	5/A	4.3	20	8	5.4	50	7	2	1	3	1	1	2	34
I	32	5/B	2.6	49	4	7.6	56	9	3	1	3	1	0	1	33
I	33	5/C	10.0	80	10	9.4	60	10	3	3	3	1	1	2	50
I	34	5/A		22	12	3.6	50	17	3	3	3	2	1	2	39
I	35	5/B	1.1	16	8	4.1	49	10	2	3	3	2	2	0	35
I	36	5/C	10.0	18	24	10.0	76	60	3	3	3	3	1	2	56
I	37	5/A	1.6	6	2	2.6	5	4	2	2	2	1	1	2	27
I	38	5/B	2.9	6	6	5.4	3	3	3	2	2	0	1	1	28
I	39	5/C	10.0	24	28	10.0	8	8	3	3	3	1	1	2	48
I	40	15/A	10.0	40	50	9.6	21	28	3	3	3	3	1	2	54
I	41	15/B	10.0	12	10	8.8	18	20	3	3	3	3	1	2	51
I	42	15/C	10.0	14	12	10.0	15	13	3	3	3	3	2	3	57

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